Top Quark Studies and Searches for New Phenomena at the Tevatron

XXVIII SLAC Summer Institute on Particle Physics, Stanford, California

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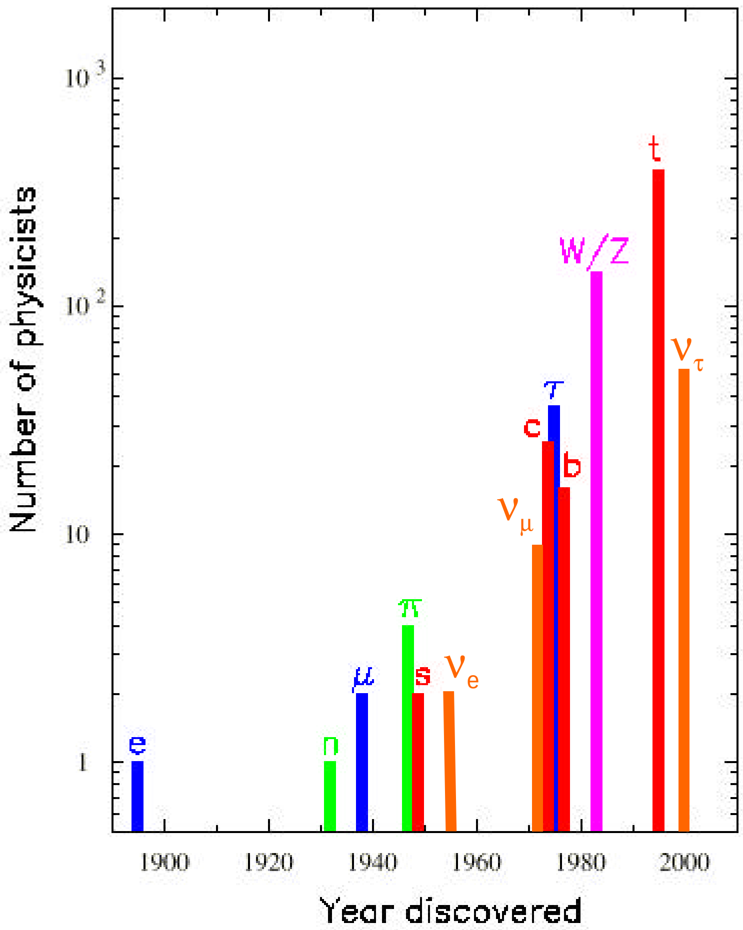
August 24, 2000

outline - the standard model (& beyond?)

- a missing piece found (Standard Model top)
  - *SM expectations and the Tevatron*
  - *mass status and M_t vs. M_W — constraints on M_H*
  - *cross section results*
  - *recent improvements*
- top secrets unfold
  - *limits on single top production & V_{tb}*
  - *hints of bare quark properties in spin correlations*
  - *W helicity*
- top and new phenomena
  - *checking tt production: p_T distributions & M_{tt}*
  - *Higgs Disappearance*
- survey of exotics searches

status of SM

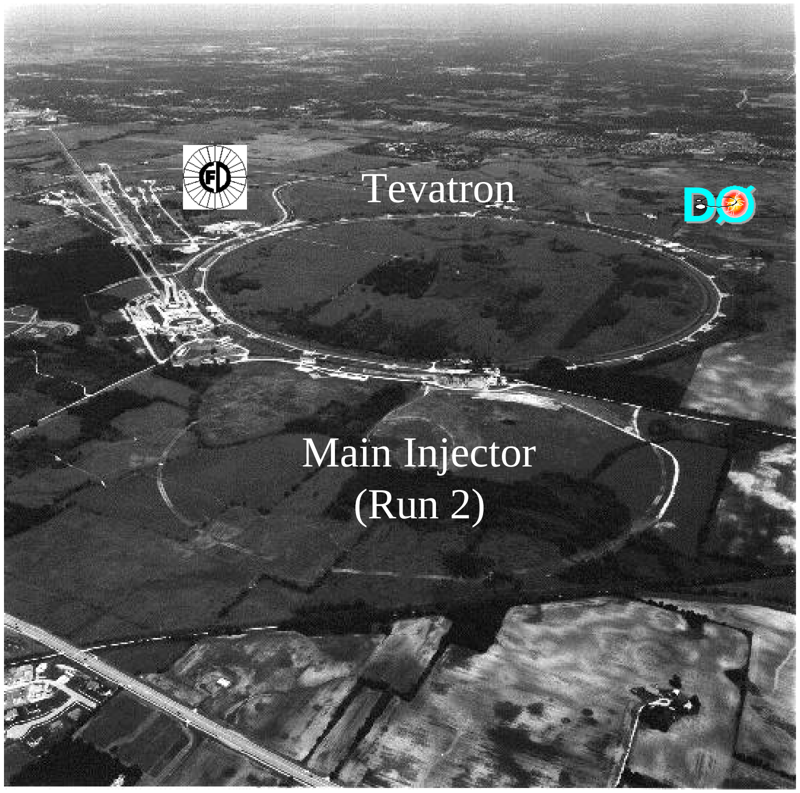


- SM is dramatically validated with discovery of last of fundamental constituents

  top quark & W/Z vector Bosons
- each new piece of the SM table demanded larger collaborations of physicists!
- trend continues as we search the Higgs sector

  potential for significant breakthroughs still at hand

the Tevatron



accelerator parameters	Run I	Run II
N_p (# of protons/bunch)	2×10^{11}	3×10^{11}
N_p (# of antiprotons/bunch)	6×10^{10}	6×10^{10}
B (# bunches in ring)	6	36
spacing	3.5 μs	296 ns
f_o (frequency)	50 kHz	50 kHz
σ^2 ("area" of beam)	3×10^{-5} cm^3	2×10^{-5} cm^3
<Instantaneous Luminosity>	1.6×10^{31} /cm^{2}s	2×10^{32} /cm^{2}s

$$L = \frac{N_p N_{\bar{p}} B f_o}{4 p s^2} \quad particles / cm^2 s$$

$$\mathcal{L} = \int L dt$$

		E_p	E_{cm}
Run I	(1992-1995)	**900 GeV**	**1.8 TeV**
Run II	(2001-2007)	**1.0 TeV**	**2.0 TeV**
LHC	(2006-20??)	**7.0 TeV**	**14 TeV**

	Run I	**Run II**
$\mathcal{L}$	**0.1** fb^{-1}	**2** fb^{-1}
σ_{tt}	**~5** pb	**~7** pb
N (top pairs)	**500**	**14000**

1 barn (b) = 10^{-24} cm^2 , 1 fb = 10^{-15} b

production cross sections at $\sqrt{s}$ = 1.8 TeV

- interesting processes have small cross sections

  need: high luminosity

  quick decisions

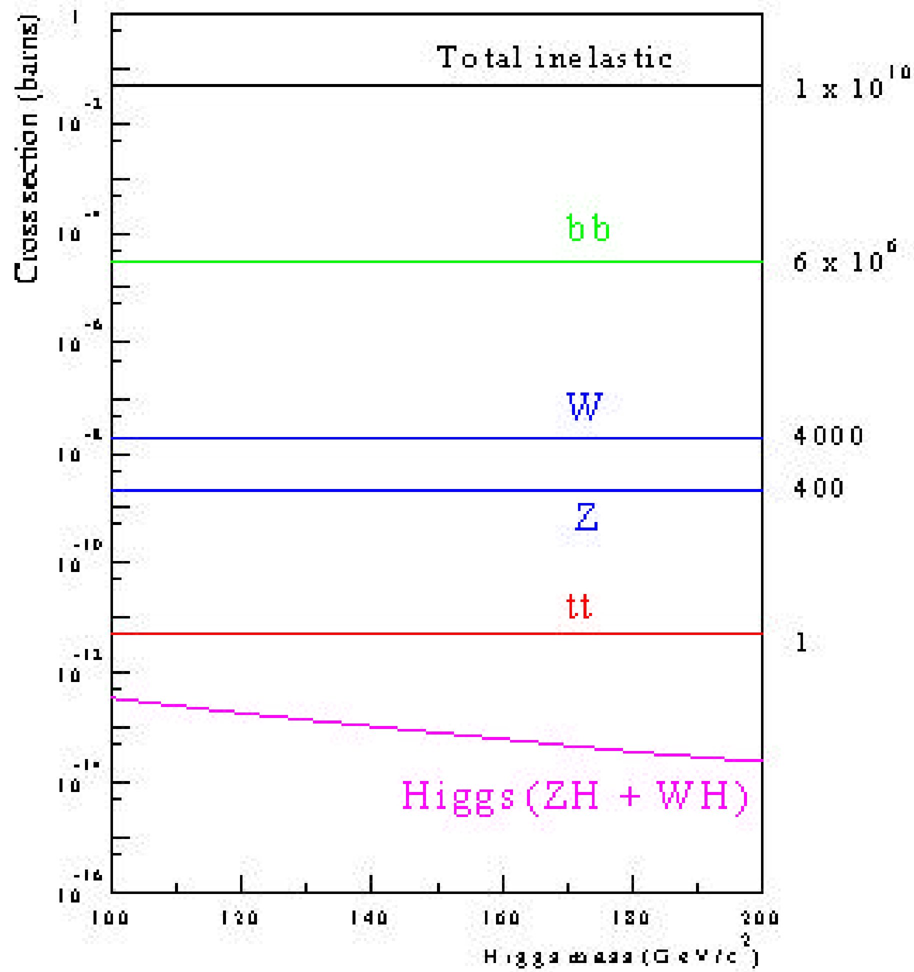
  ~ 3x10^5 events per second (10^7 for Run II)

- Run I production at maximum luminosity:

  one tt event every three hours

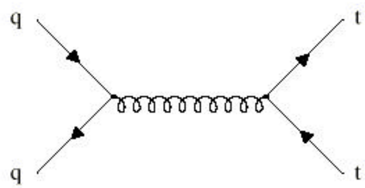
  one W event every three minutes

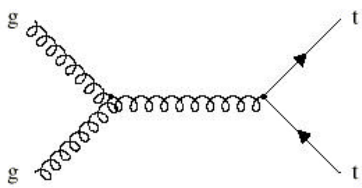
- problem: many competing background processes

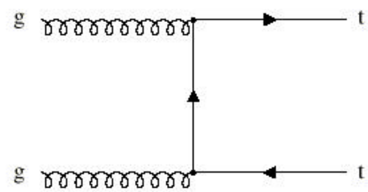


top production cross section (pb)

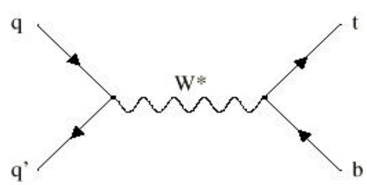
pair production

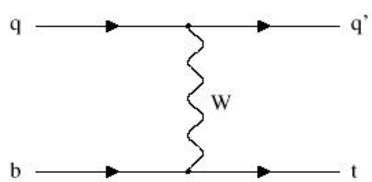


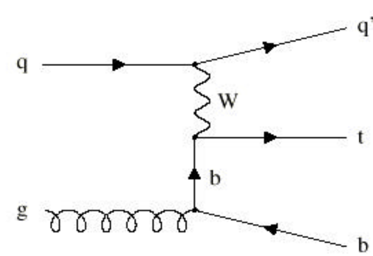


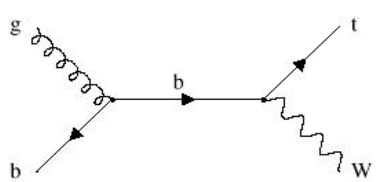


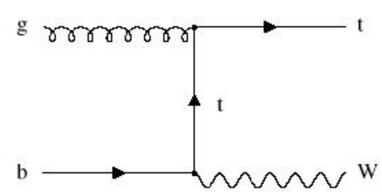
single top









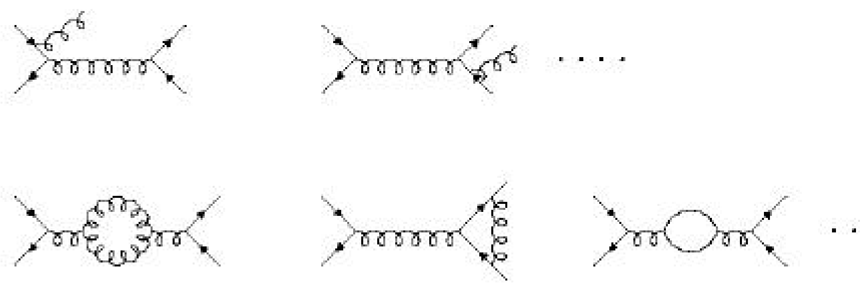


	Run I $p\bar{p}$ 1.8 TeV	Run I $p\bar{p}$ 2.0 TeV	LHC pp 14 TeV
pair production ($q\bar{q}$)	90%	85%	5%
pair production (gg)	10%	15%	95%
pair production (total)	5.0	7.0	800
single top (W^*)	0.73	0.88	10.2
single top (W-gluon)	1.7	2.4	245
single top (tW)	0.07	0.12	62

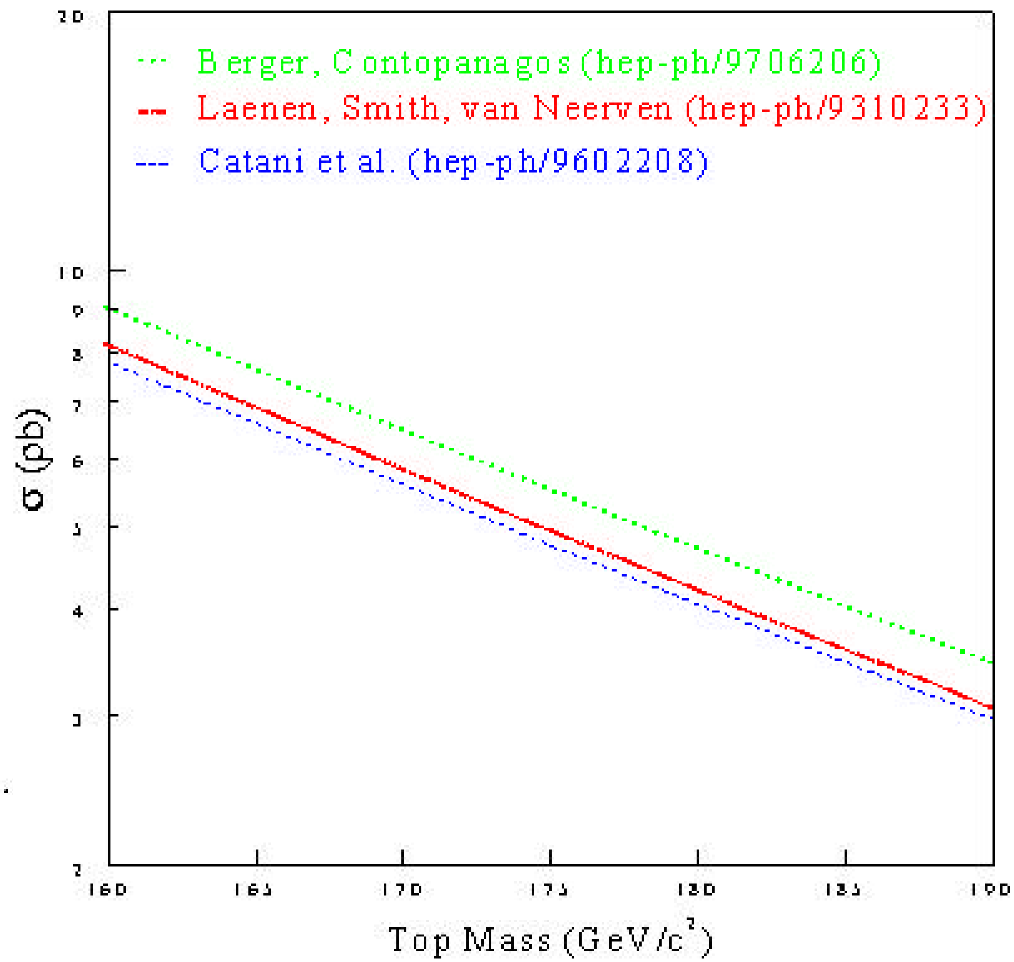
(for M_t=175 GeV)

top pair production at √s = 1.8 TeV

- calculated using perturbative QCD to NLO $(O(\alpha_s^3))$ and including soft gluon resummation
- NLO correction contribute about 20% to the cross section



- overall theoretical uncertainty is less that 20%



top quark decay

- assuming V-A coupling with CKM mixing parameter $|V_{tb}| = 1$ for the decay vertex $t \to bW$ (for LO)

  $\Gamma(t \to bW) \approx 175\ \mathrm{MeV}(M_t/M_W)^3 \approx 1.5\ \mathrm{GeV}$ $\qquad (M_t, M_W >> M_b)$

  So: $\tau(\mathrm{top}) \approx 4 \times 10^{-25}\ s$

- aon-perturbative QCD hadronization takes place in a time of order:

  $1/\Lambda_{QCD} \sim (100\mathrm{MeV})^{-1} \sim 10^{-23}\ s$

  $\rightarrow$ the top quark decays as a *free* quark

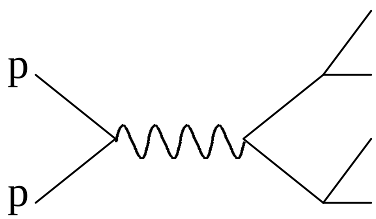
  (no toponium spectroscopy, no top hadrons)

  $\rightarrow$ original spin-½ state is preserved throughout decay

- $t \to cW$ *and* $t \to sW$ allowed but suppressed by factors of $\sim 10^{-3}$ and 5×10^{-5}, respectively

top pair decay signature

decay signatures and branching fractions:



	W Decay Mode			
W	$l\nu$	jj	$l\nu$	jj
b	b	b	b	b
W	$l\nu$	$l\nu$	jj	jj
b	b	b	b	b

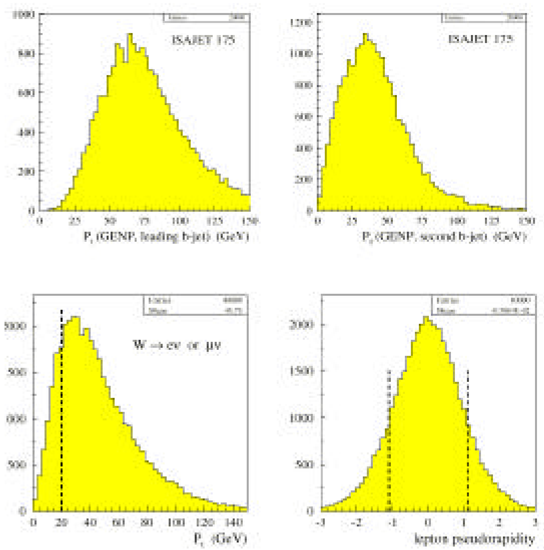
$\mathrm{BR}(W \to \ell\nu) = 3/9$

$\mathrm{BR}(W \to q\bar{q}') = 6/9$

All Jets Huge QCD Background

Lepton + Jets Good cross section and manageable backgrounds (W+jets)

Dilepton Very small backgrounds, but very small cross section



decay signatures

- dilepton: 2 high p_t leptons, 2 *b*-jets, large Et

  BR(ee,mm,em) =5%

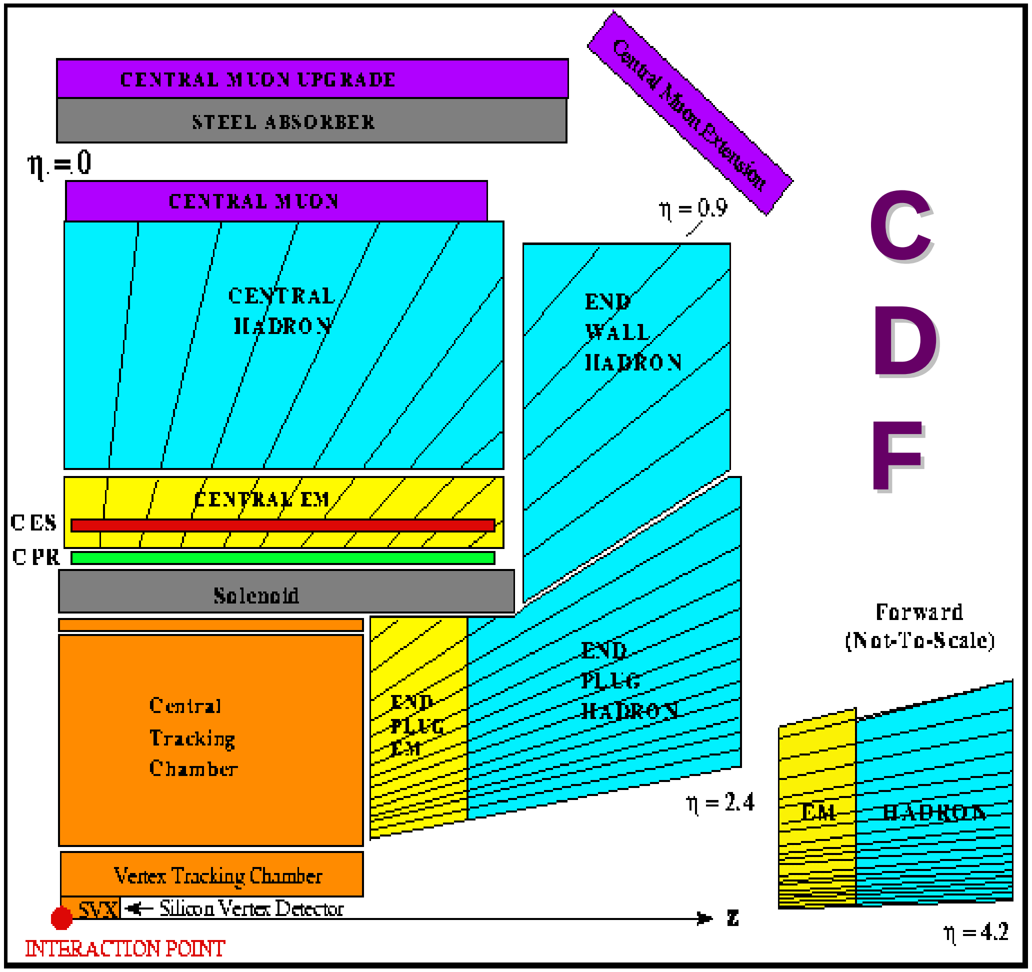
- lepton+jets: 1 high p_t lepton, 4 jets, large Et

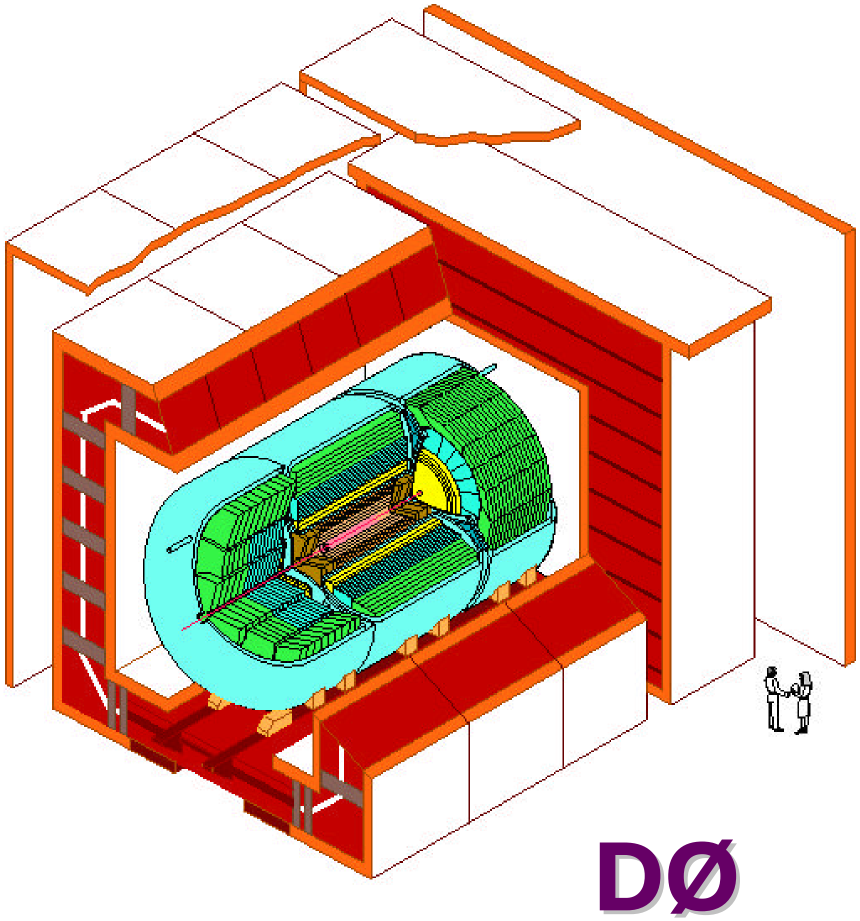
  BR(e,m +jets) =30%

- all hadronic: 6 jets (including 2 *b*-jets)

  BR= 44%

run I detectors: CDF and DØ





“typical” $t\bar{t}$ candidate event (CDF)

e + 4 jet event

40758_44414

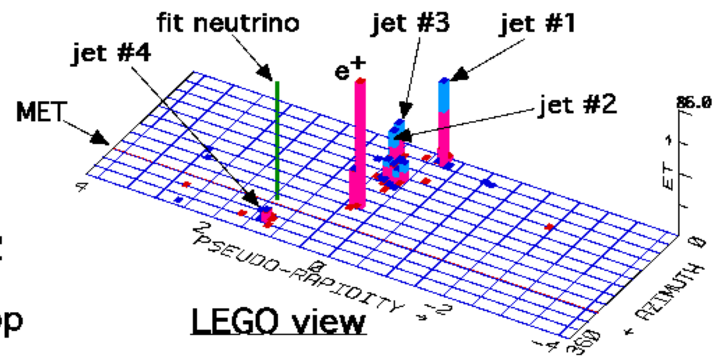
24-September, 1992

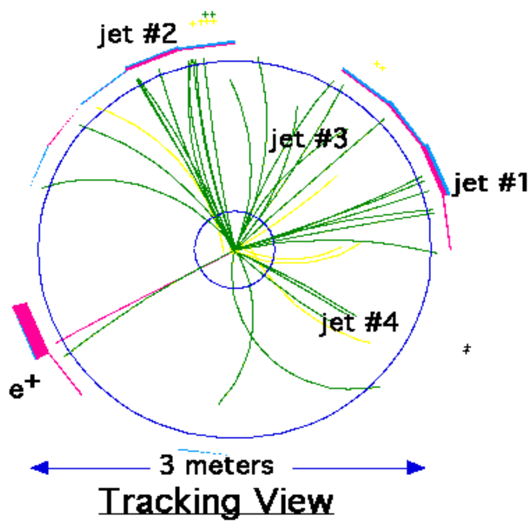
TWO jets tagged by SVX

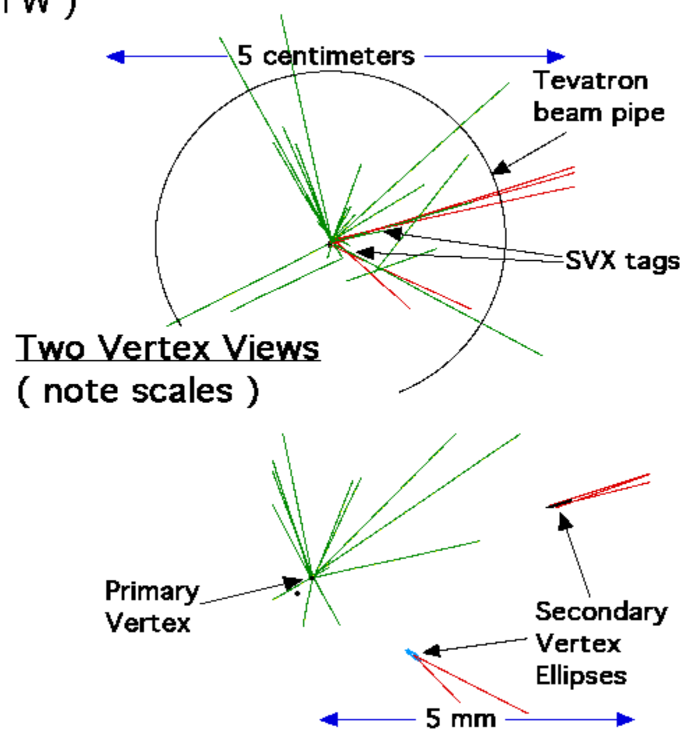
fit top mass is 175±10 GeV/c^2

e^+, Missing E_t, jet #4 from top

jets 1,2,3 from top (2&3 from W)

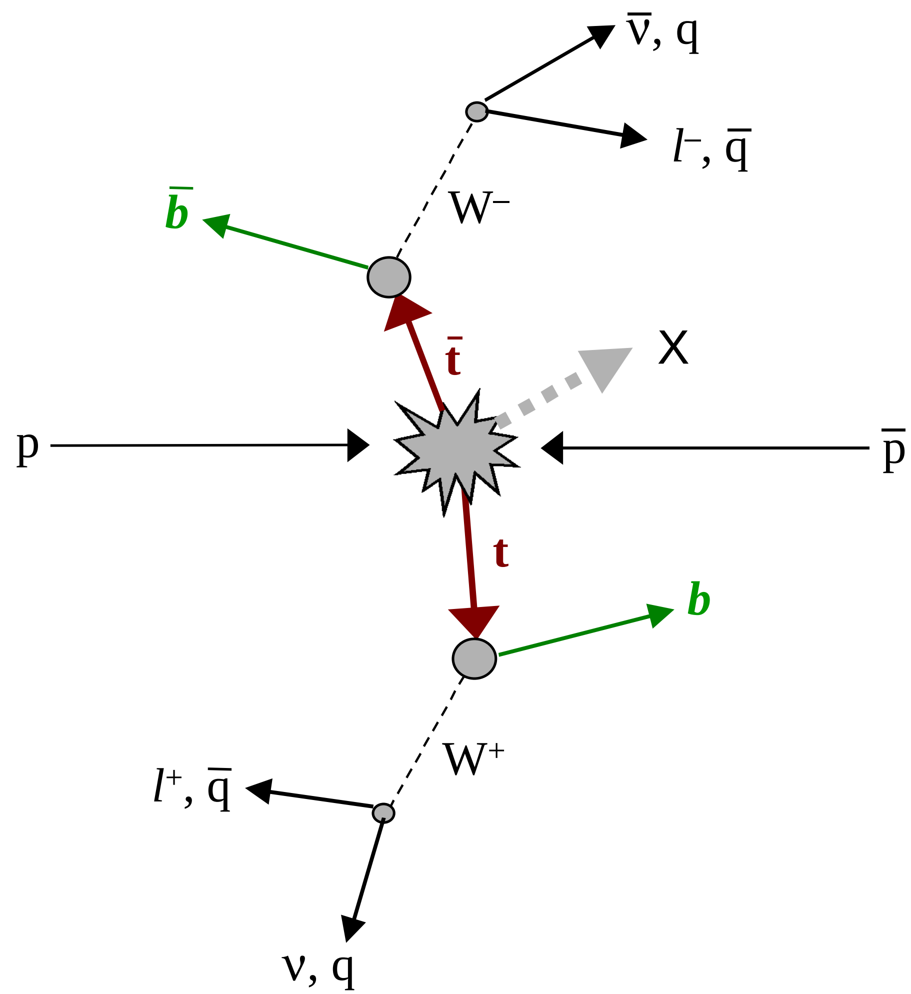






top secrets

- intrinsic properties
  - *top quark mass*
  - *top spin polarization*
  - *W helicity*
- production
  - *cross section*
  - *resonance production?*
  - *production kinematics*
- decay
  - *decay modes*
  - *branching ratios*
  - *CKM matrix element V_{tb}*
  - *rare decays*
  - *non-SM decays*



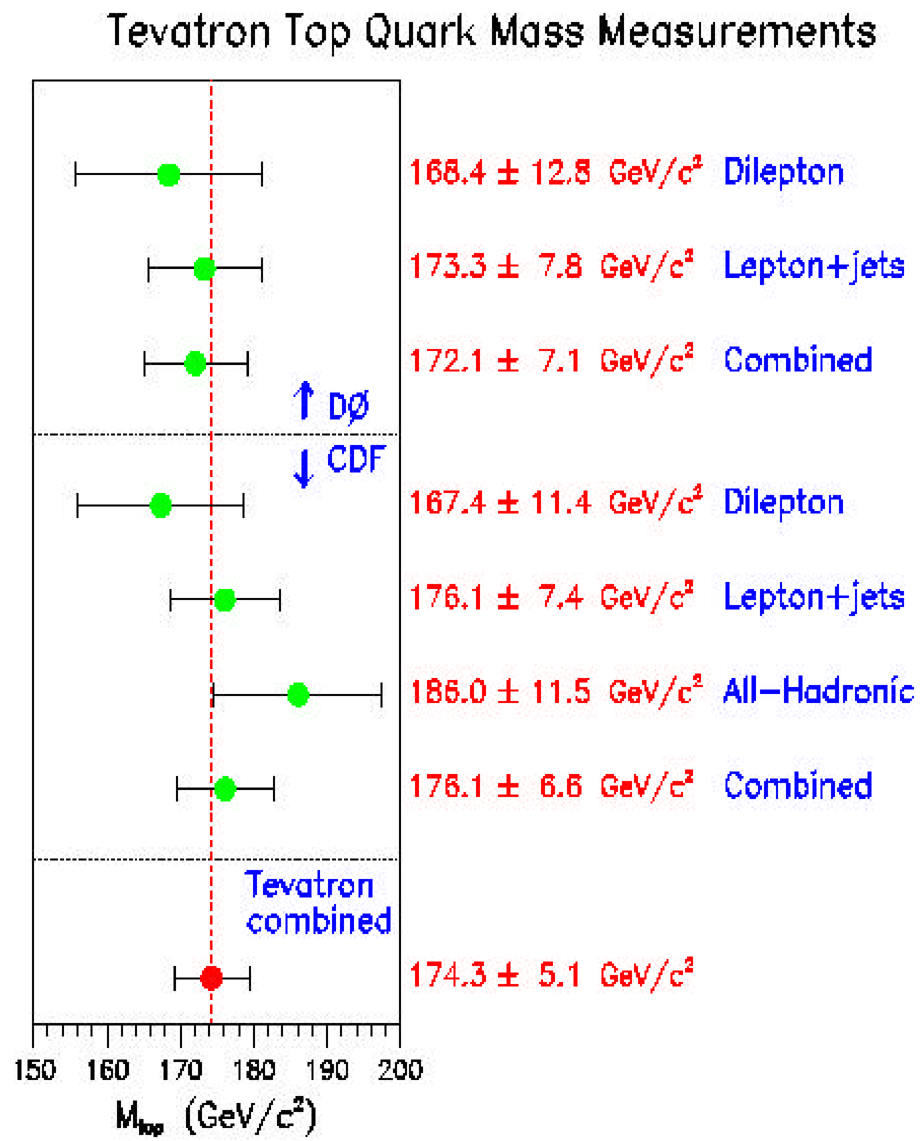
top mass measurements

- SM electroweak fits give

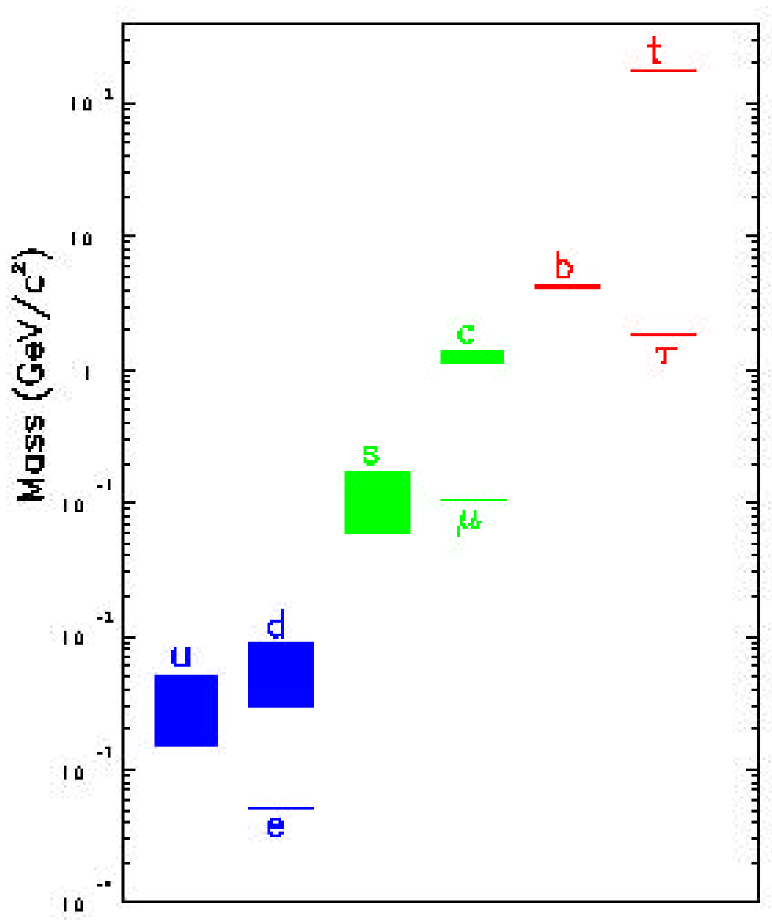
$M_t = 170 \pm 7 (\pm 14)$ GeV PDG'98

assuming $M_H = M_Z$ (=300GeV)

- direct mass measurements are consistent with SM fits
- what can M_t tell us?
  - *fundamental parameter of SM*
  - *top quark's coupling to Higgs, $tt \sim m_t^2/M_W^2$*
  - *radiative corrections sensitive to the top mass: W boson mass depend on M_W, M_Z, M_t and so precise measurements constrain M_H*
- top quark mass is best measured of all quarks (~3% precision)



spectrum of quark and lepton masses



- approximately 5 orders of magnitude range in quark masses

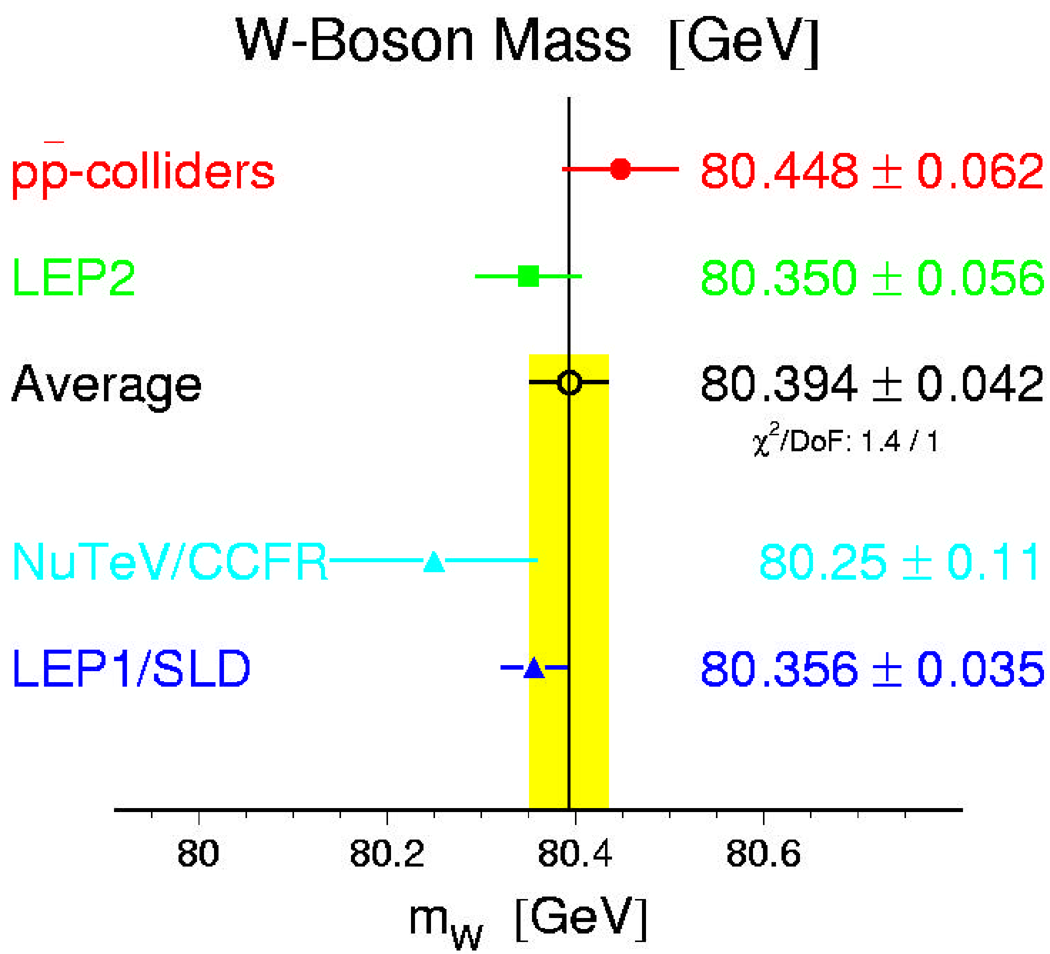
M_W

DØ Average

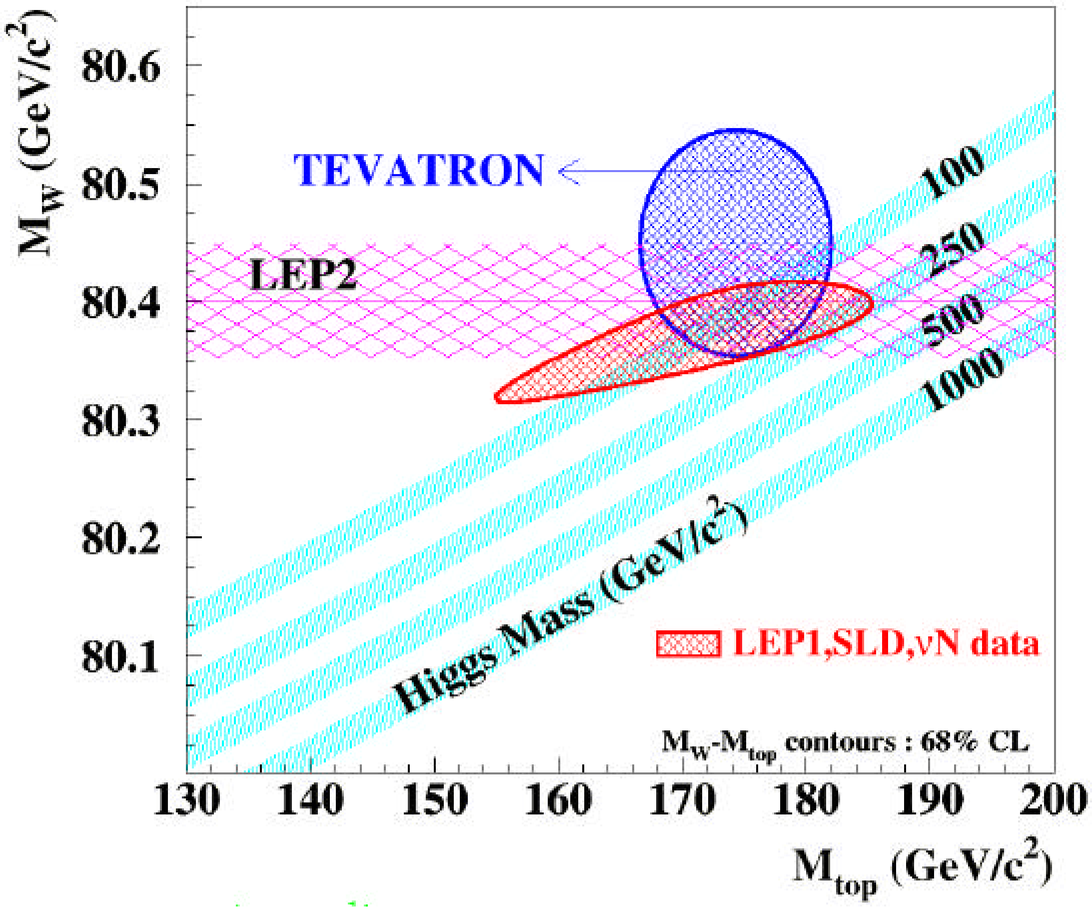
80.474 ± 0.093

CDF Average

80.433 ± 0.079



constraints on M_H



measured run I
top pair production cross section at √s = 1.8 TeV

$$\sigma(p\bar{p} \to t\bar{t} \to \text{channel}_i) = \frac{N^i_{obs} - N^i_{bkgd}}{\epsilon^i \cdot \int L\,dt}$$

- σ(t t) changes since publication:
- CDF

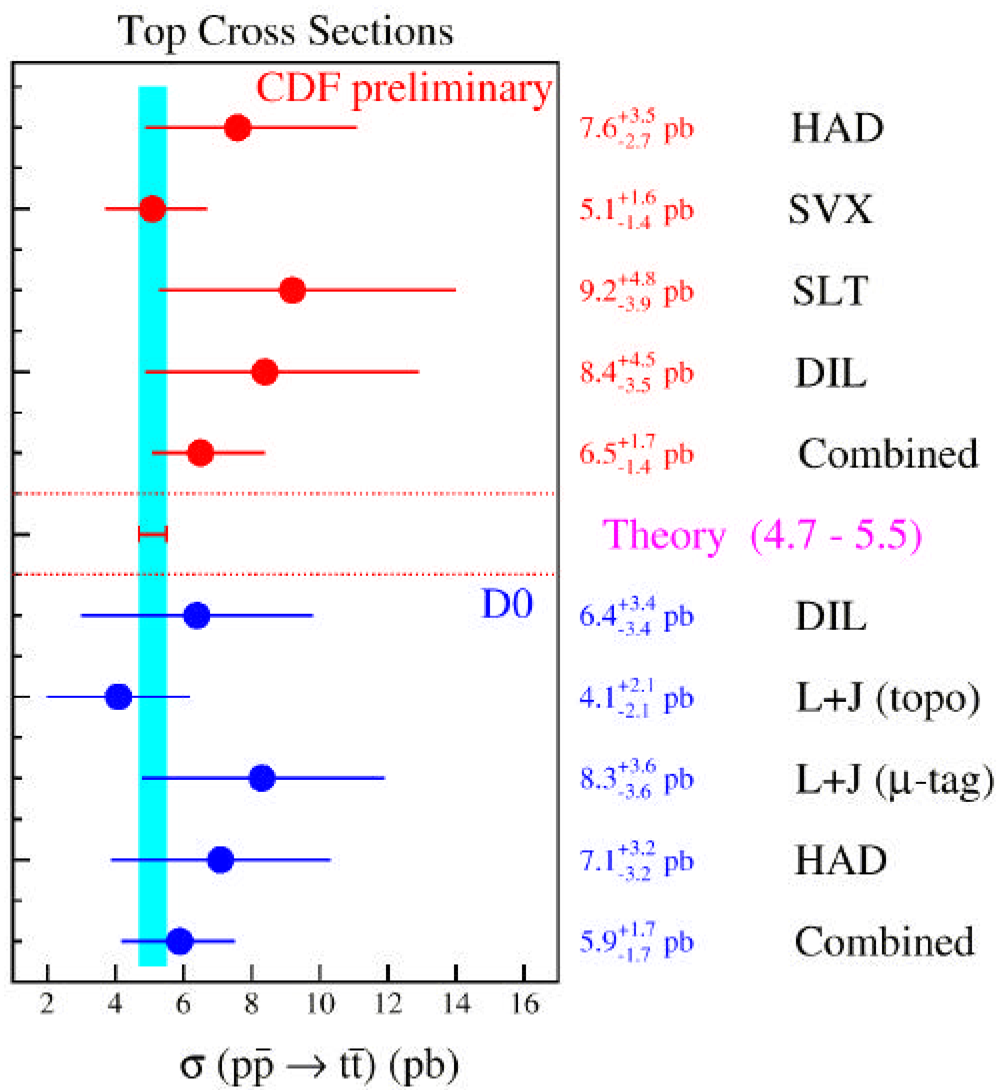
  has updated the b-tagging:

  systematic error due to mistagging of b-vertex to 10% down from 40%

  all of CDF's results reflect an updated Luminosity.
- DØ's results are unchanged

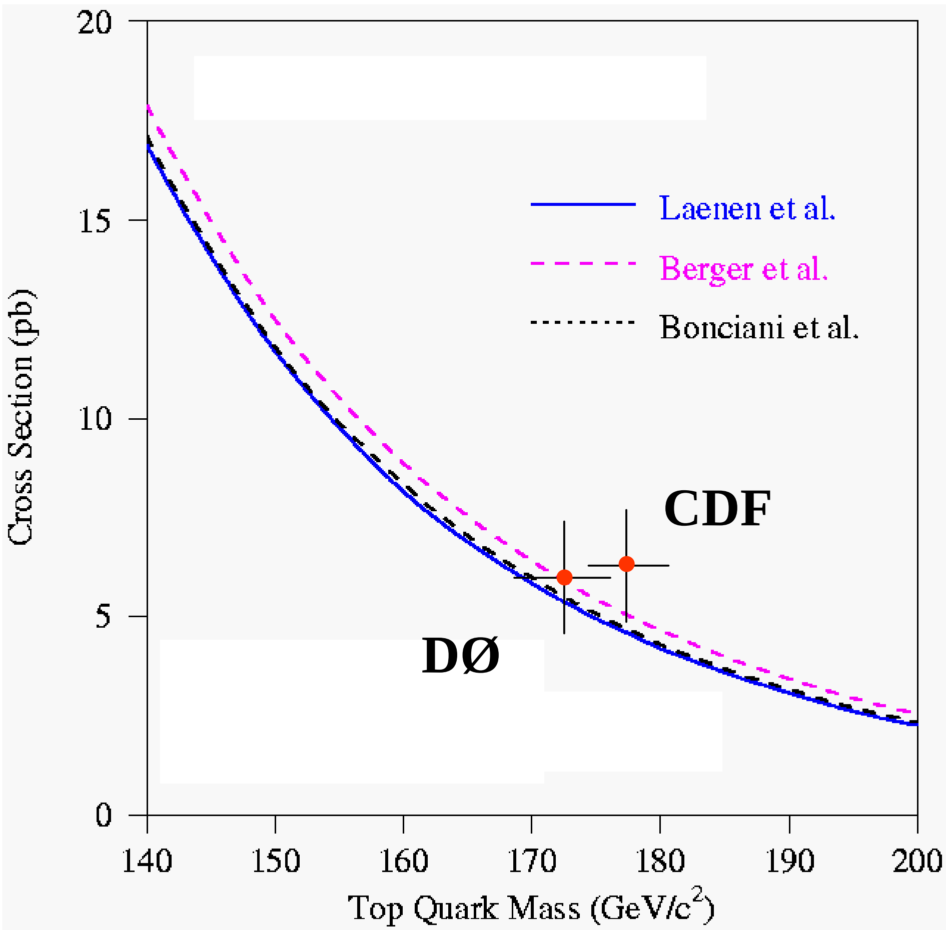
$$\text{CDF } s\,(t\bar{t}) = 6.5^{+1.7}_{-1.4}\,\text{pb}$$

$$\text{DØ } s\,(t\bar{t}) = 5.9 \pm 1.7\,\text{pb}$$



CDF's old value: $s\,(t\bar{t}) = 7.6^{+1.8}_{-1.5}$

top cross section vs mass



CDF M_t=176.0 ± 6.5 GeV/c^2

DØ M_t=172.1 ± 7.1 GeV/c^2

neural net analysis of $tt \rightarrow e\mu$

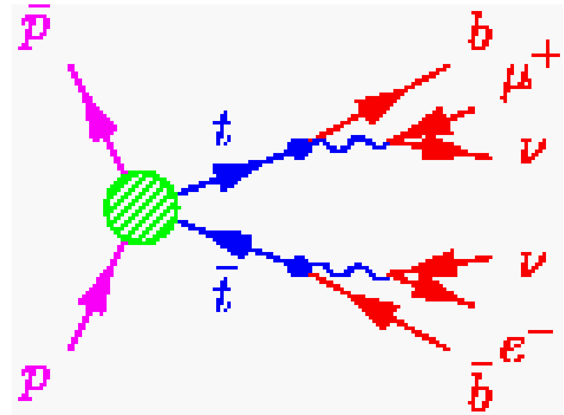
— eμ is a golden channel

low backgrounds

but, low BR (2.5%)

— long standing standard analysis

can multivariate techniques *do better?*



Standard analysis

- *cuts on E_T of electron, muon, missing E_T, jets, and total energy in event (H_T).*

NN analysis:

- *release the jet E_T and missing E_T cuts*
- *remove the H_T requirement*

feed forward NN trained on simulated signal and background

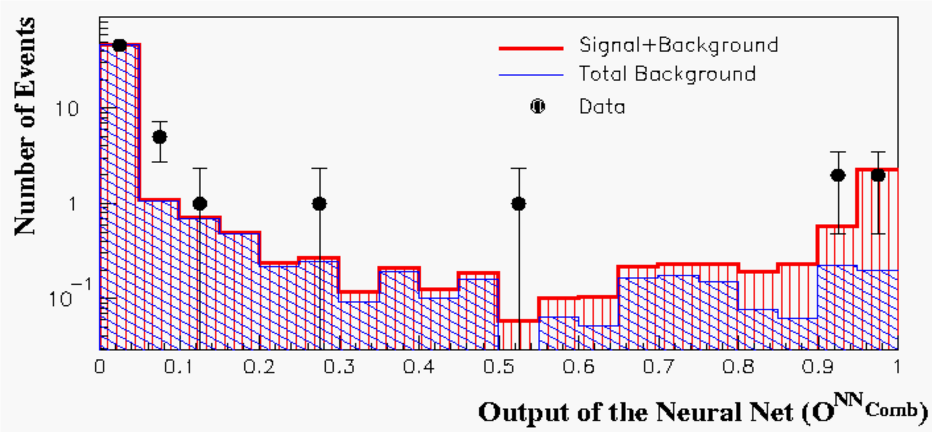
QCD, Z®tt®em, and WW®em

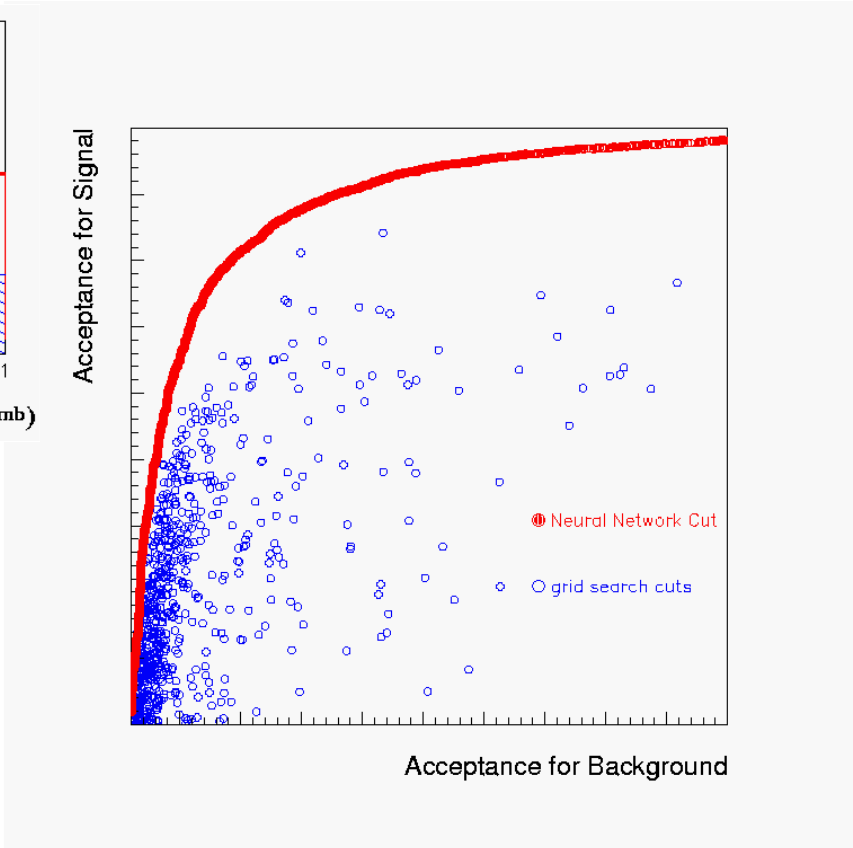
variables:

$$E_T^e \qquad E_T^{jet1/2} \qquad E_T$$

$$\sum E_T^{jet} \qquad M(e,m) \qquad \Delta J(e,m)$$

neural net analysis of $t\bar{t} \to e\mu$





— standard analysis was optimized using *RGS*

RGS is a selection-cut phase-space optimizer

— NN is about 10% better than the standard analysis

broad range of top masses tested

NN analysis
$\sigma(t\bar{t}) = 8.8 \pm 5.1\text{pb}$
relative uncertainly: 60%

conventional analysis
$\sigma(t\bar{t}) = 7.1 \pm 4.8\text{pb}$
relative uncertainly: 68%

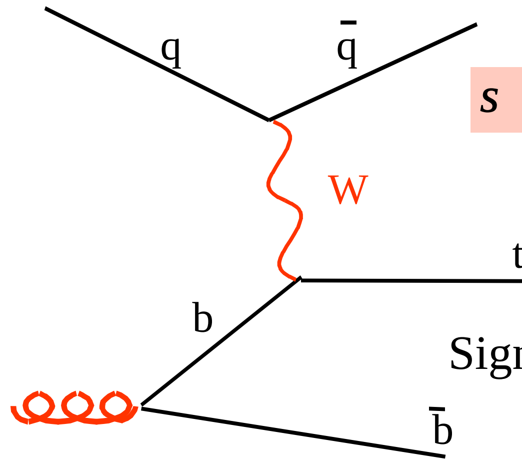
search for single top production

- not observed in run I
- signal

  one or two hard b-jets

  W decay products
- search channel: lepton +jets

  W ® eν, μν   BR=22%
- backgrounds much worse than for tt include: W+jets, mistags, and tt production!



$s = 1.70 \pm 0.09\text{pb}$

Stelzer 1998

Signal is W+b+q

After detector efficiency/acceptance

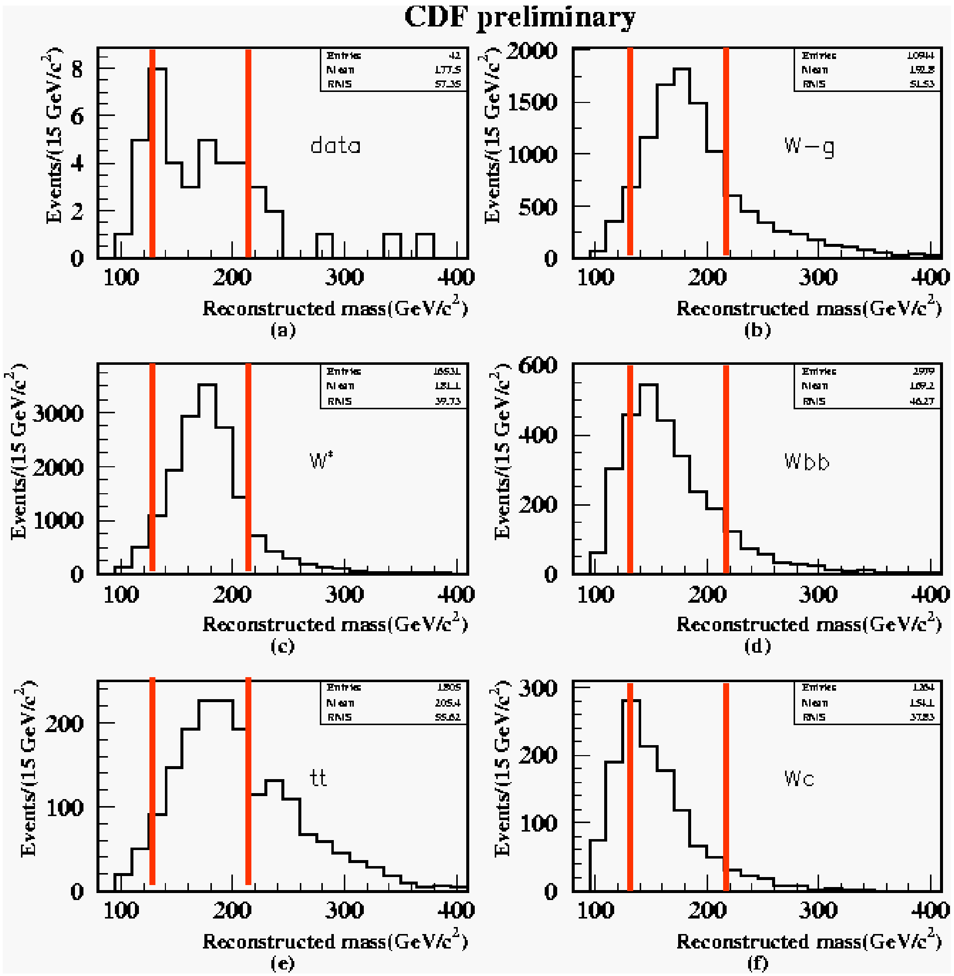
Expect only 1.2 ± 0.3 events!

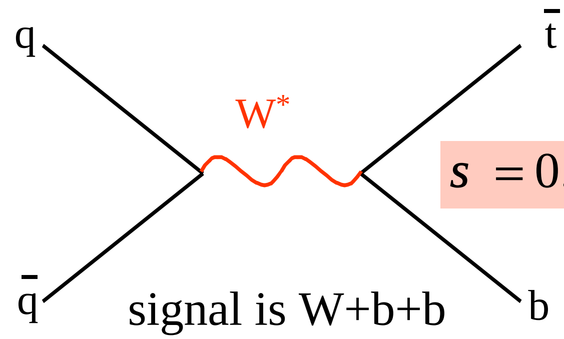
Expected total background: 12.9 ± 2.1
Observe 15 events

$s_{W-\text{glu}} < 15.4\text{pb}$ @ 95% CL

Preliminary

search for single top production





$s = 0.73 \pm 0.04\text{pb}$

signal is W+b+b

Smith 1996

after detector efficiency/acceptance

expect only 1.0 ± 0.3 events!

Expected total background: 29.7± 2.1
Observe 42 events

$s_{s-W} < 15.8\text{pb}$@ 95% CL

Preliminary

single top

- CDF run I limits:

  CDF's best result is obtained from a fit to the total E_t spectrum of W+1,2,3 jet events.

  σ(single top) < 13.5 pb @ 95% CL

- still ~ 6 x above SM expectation

- **run II** projections (2fb^{-1}):

  100-200 events per experiment

  increased data set size allows for better selection cuts

  - *better signal-to-background ratio*

- measurements

  σ (20% error)

  partial widths G(t®WX)

  V_{tb} (12% error) (independent of number of generations)

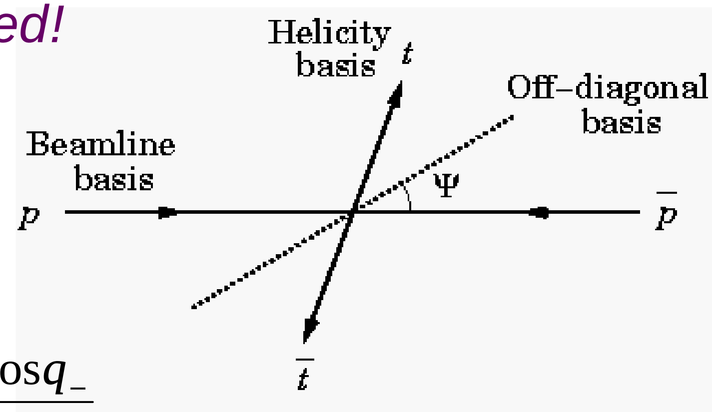
spin correlation

- top spin is not polarized at Tevatron

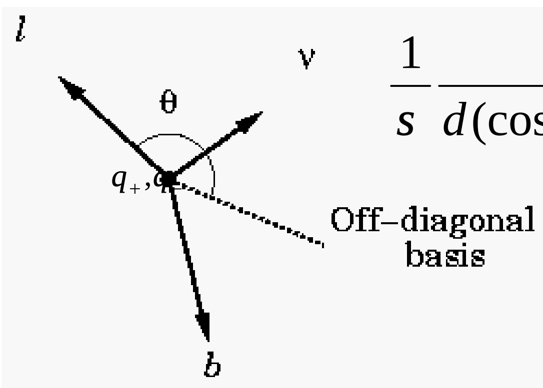
  but spins of the two top quarks are correlated!
- spin has a quantization axis

  off diagonal basis

  [Mahlon and Parke, PLB411, 173 (1997)]



Center–of–mass frame



Top quark rest frame

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_+)d(\cos\theta_-)} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}$$

Correlation information is in κ.

SM Prediction for TeV ~ 0.9

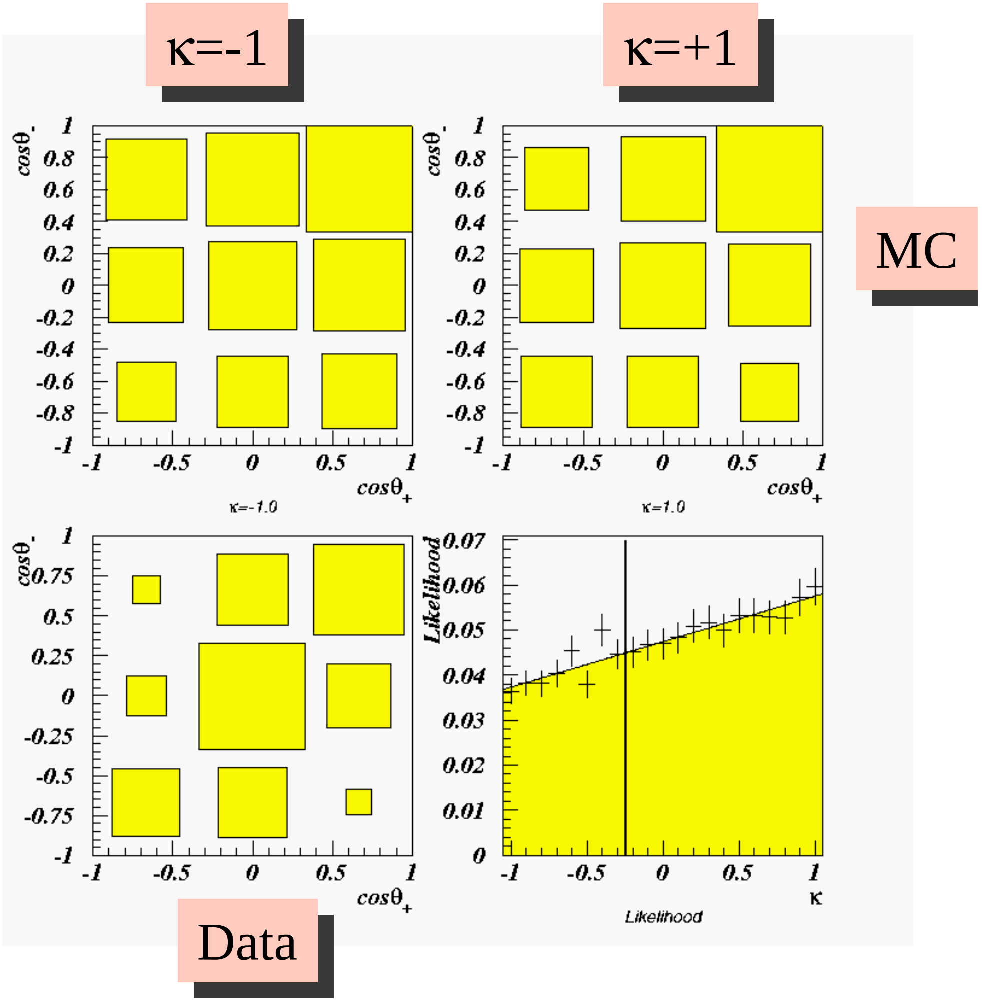
spin correlation

- events are reconstructed using the same method as for the dilepton mass reconstruction

  Events are underconstrained

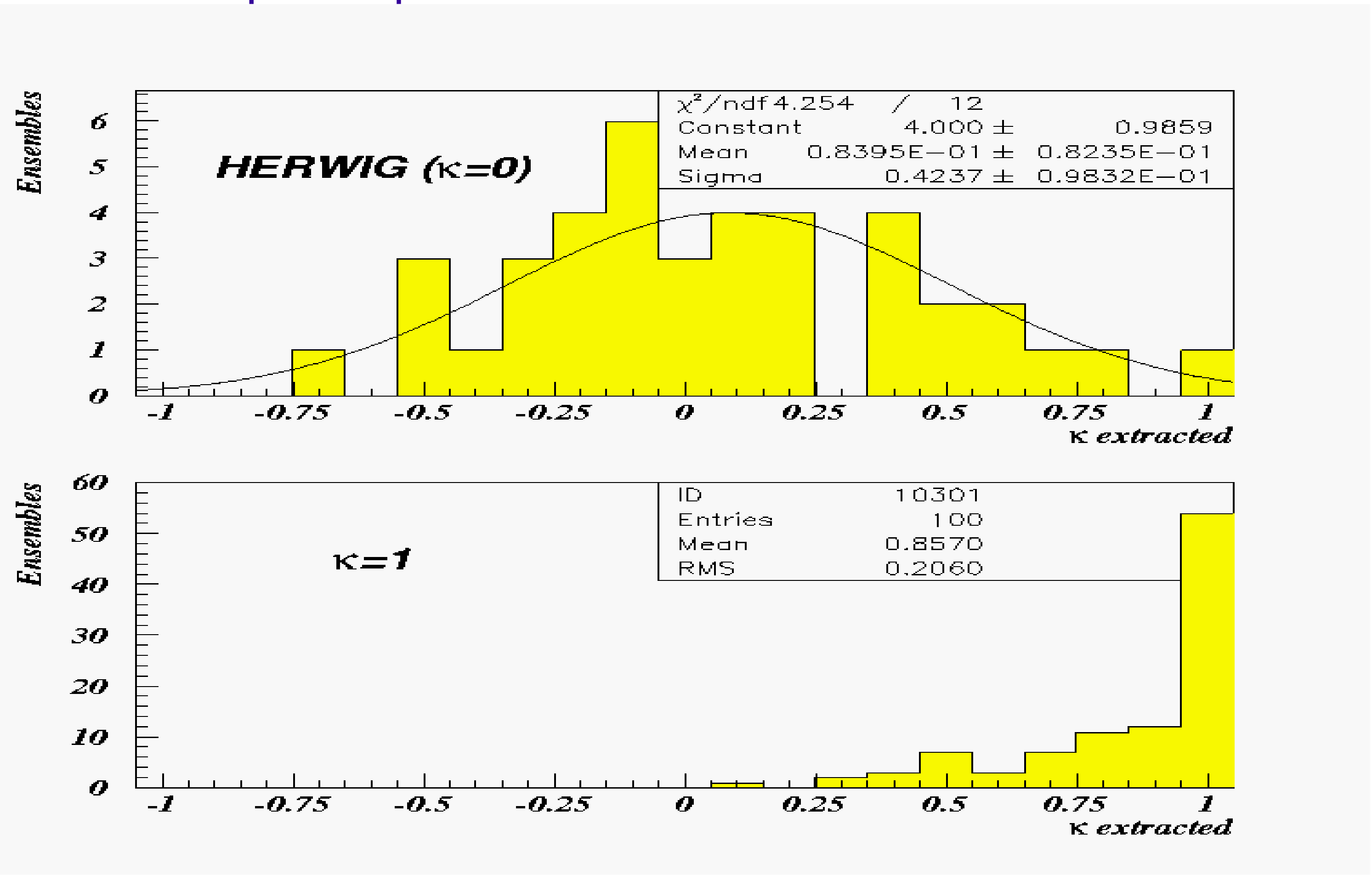
- 6 DØ dilepton candidates
- *binned 2D likelihood fit*

$\kappa > -0.25$ @ 68% CL



spin correlation in run II

~ 150 dilepton events per experiment

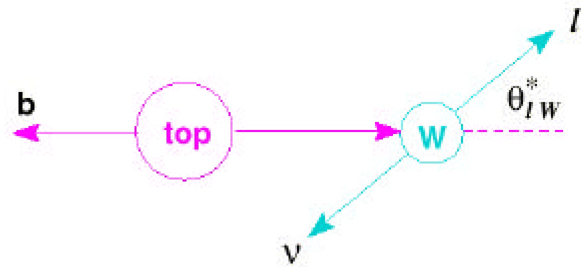


W helicity

- SM top decays only to longitudinally polarized or left-handed W

  h_W = 0 or -1

$$\frac{\mathrm{BR}(t \to bW_{\mathrm{long}})}{\mathrm{BR}(t \to bW_{\mathrm{left}})} = \frac{1}{2}\left(\frac{m_t}{m_W}\right)^2 = \frac{0.70}{0.30}$$

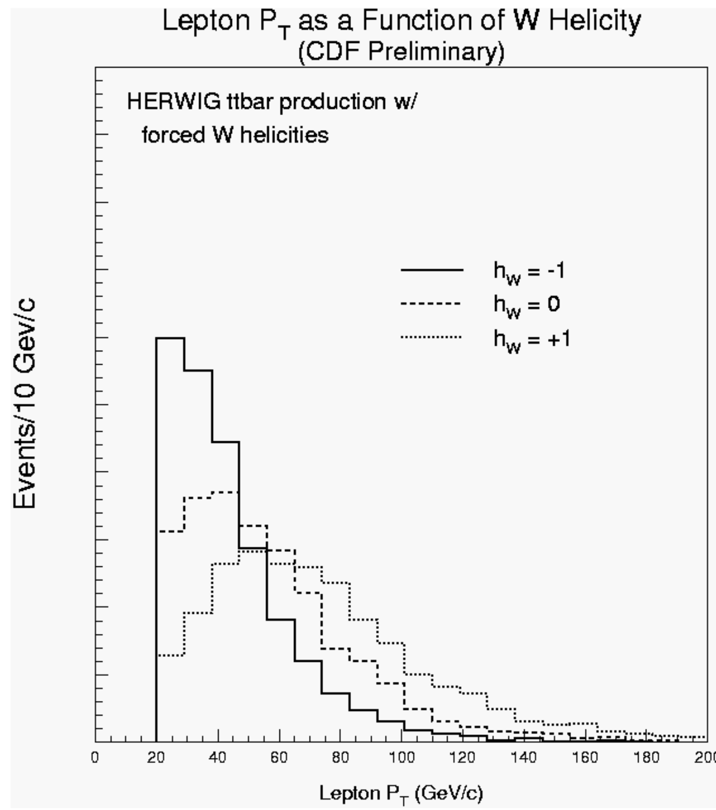


- lepton p_T distributions in *t→bln* distinguish the two helicity states.

  h_W=0: perpendicular to W momentum

  h_W=-1: Opposite to W momentum

$$|M(W_-)|^2 = \tfrac{1}{4}(1-\cos\theta^*_{\ell W})^2$$
$$|M(W_+)|^2 = \tfrac{1}{4}(1+\cos\theta^*_{\ell W})^2$$
$$|M(W_0)|^2 = \tfrac{1}{2}(\sin\theta^*_{\ell W})^2$$



- lepton p_T

  better measured than angular correlations

  unaffected by combinatorics or

  n reconstruction

W helicity

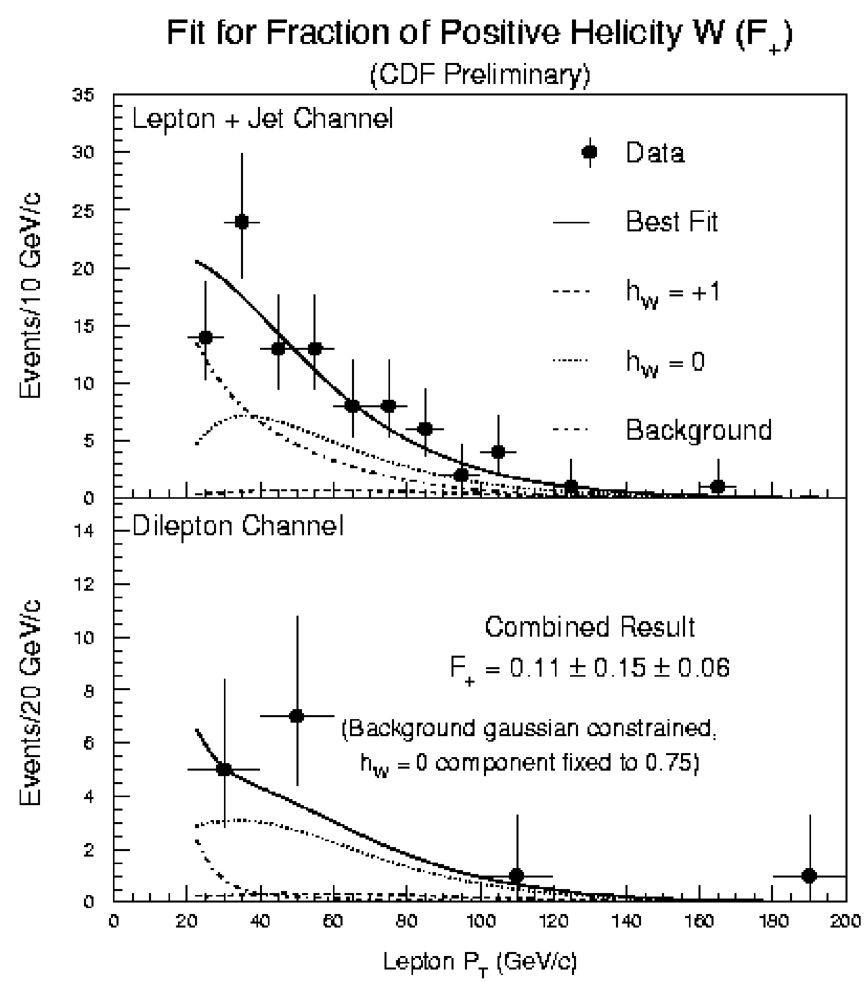
- backgrounds include W+jets, fake leptons, HF production, $Z \rightarrow tt$, and *WW*.
- unbinned maximum likelihood fit to the MC predicted expectations for longitudinal and left and background

- F_{right} determined by repeating fit with F_{long} constrained to the SM value of 0.7

$$F_{long}=0.91 \pm 0.37\ (\text{stat}) \pm 0.12\ (\text{sys})$$

$$F_{right}=0.11 \pm 0.15\ (\text{stat}) \pm 0.06\ (\text{sys})$$

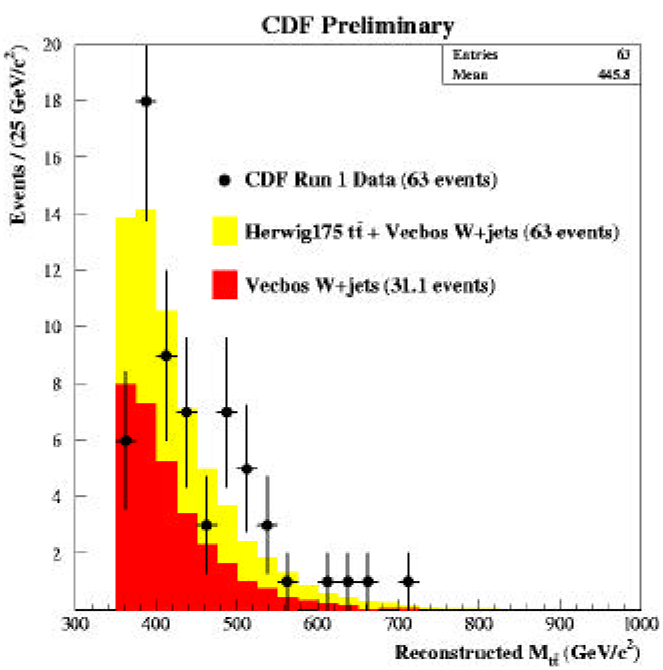
Run 2: $\delta \sim 6\%$

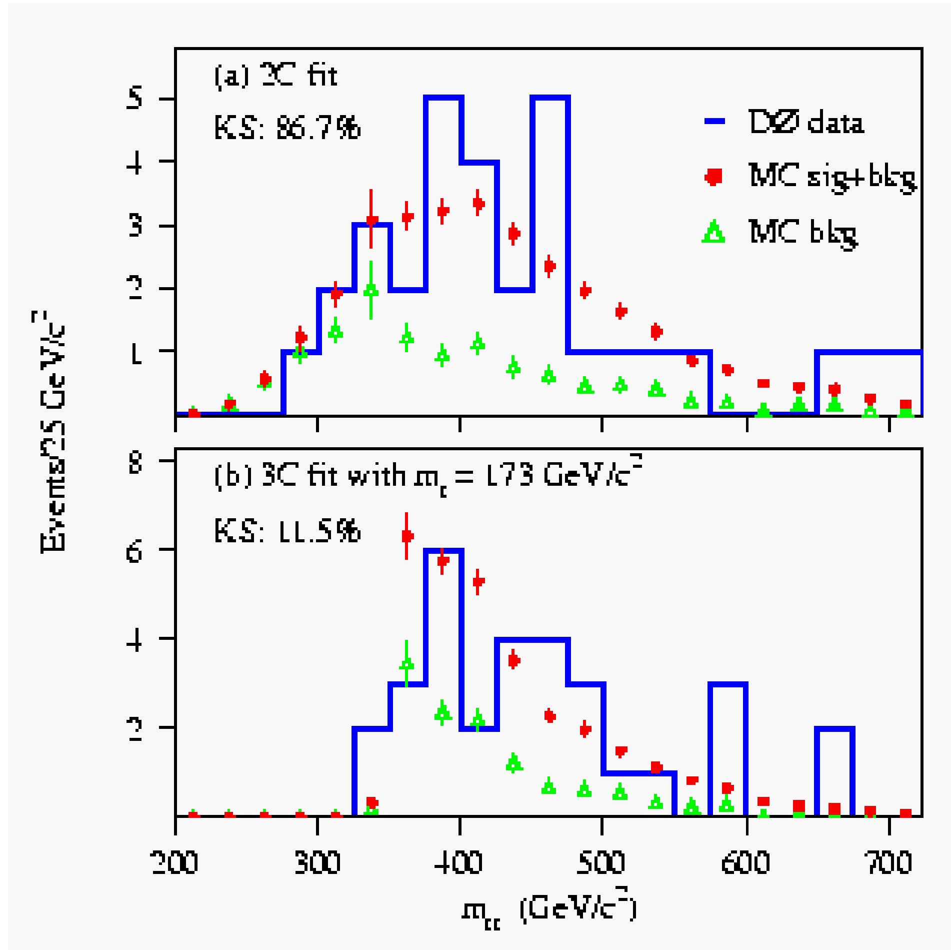


top pair invariant mass: M_{tt}

- some Technicolor theories predict existence of heavy objects that decay to tt pairs.

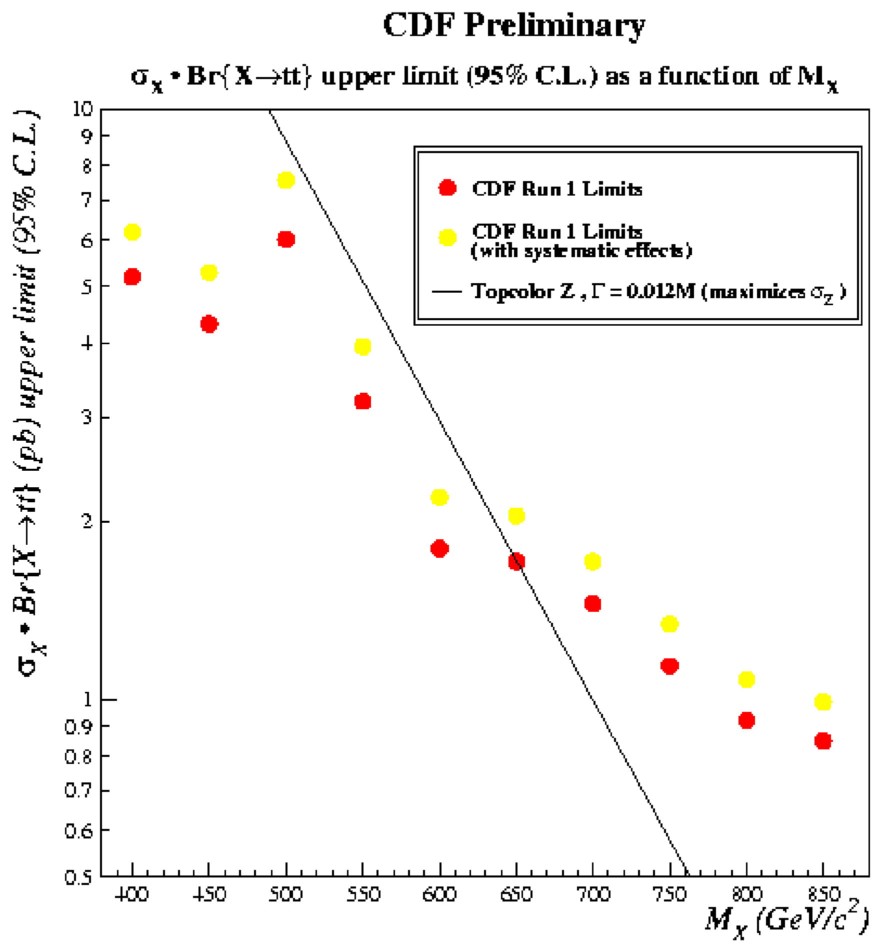
  top gluons and a Z' in topcolor assisted Technicolor.





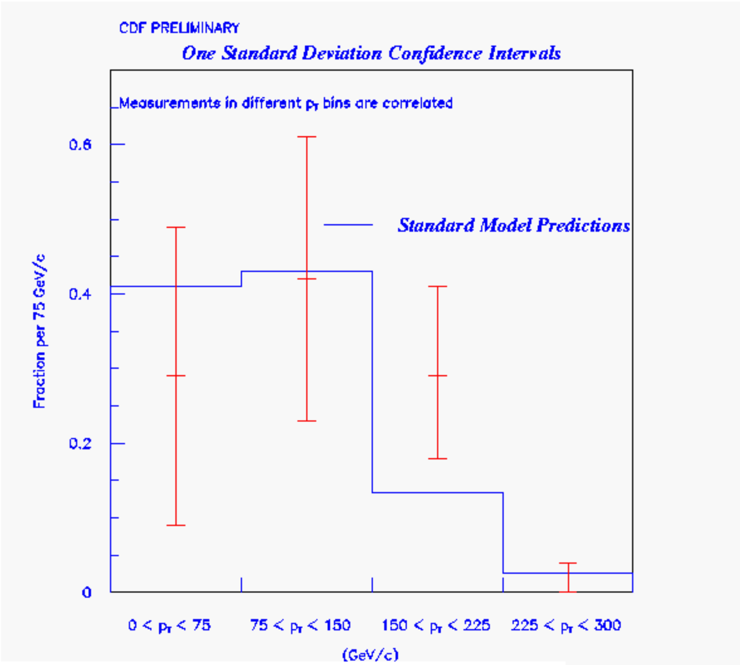
top pair invariant mass: M_{tt}

- perform binned likelihood fit using M_{tt} templates.
  - Z’ ®tt
  - *SM* tt
  - *QCD W+Jets*
- 95% CL limits obtained by mapping the likelihood as a function of N_x
- in region less than 650 GeV/c^2
  - *existence of a narrow width topcolor Z’ which maximizes the predicted Z’ production cross-section is excluded.*
- run II: in the continued absence of $Z' \rightarrow tt$ signal we will set limits on such heavy narrow resonances up to 1 TeV



top quark p_T distribution

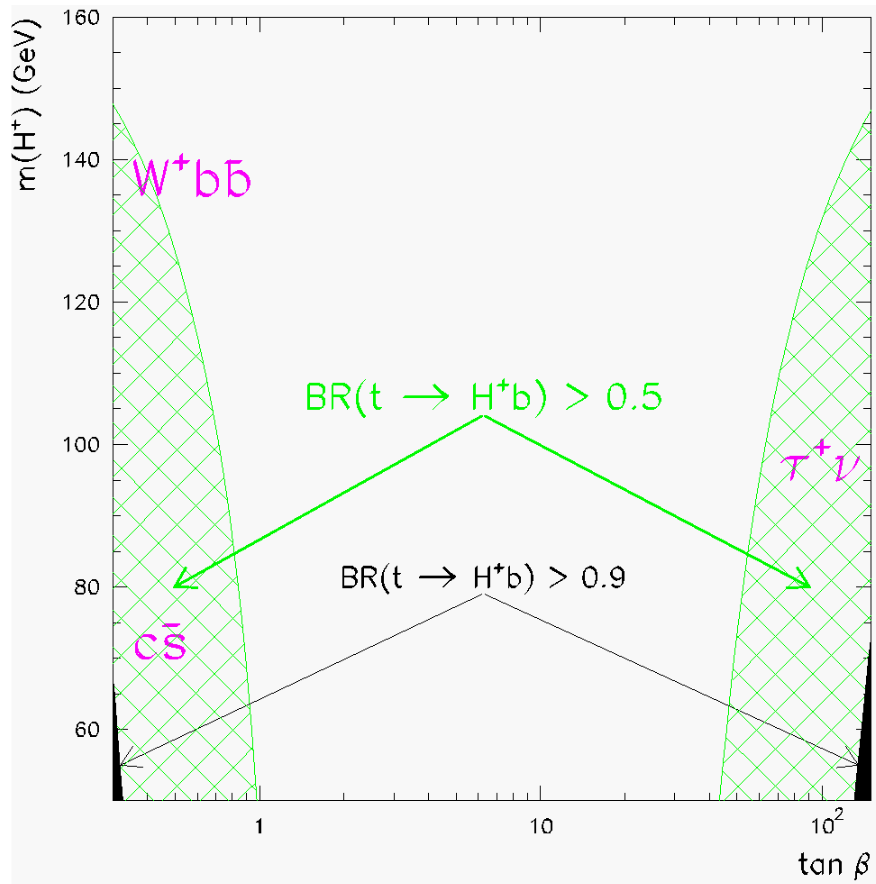
- look for deviations in the top quark production variable p_T
  - extended technicolor *predicts these deviations*
  - *R_4 is where most difference is expected*
- use standard lepton + jets sample
- unfold reconstruction smearing
  - *bin in true top p_T*
- excellent agreement with the SM
  - *work in progress to establish quantitative limits on various models.*



p_T bin	Parameter	Measurement	SM
$0 \leq p_T < 75$ GeV	R_1	$0.21^{+0.22}_{-0.21}(stat)\ ^{+0.10}_{-0.08}(syst)$	0.41
$75 \leq p_T < 150$ GeV	R_2	$0.45^{+0.23}_{-0.23}(stat)\ ^{+0.04}_{-0.07}(syst)$	0.43
$150 \leq p_T < 225$ GeV	R_3	$0.34^{+0.14}_{-0.12}(stat)\ ^{+0.07}_{-0.05}(syst)$	0.13
$225 \leq p_T < 300$ GeV	R_4	$0.000^{+0.031}_{-0.000}(stat)\ ^{+0.024}_{-0.000}(syst)$	0.025
$0 \leq p_T < 150$ GeV	$R_1 + R_2$	$0.66^{+0.17}_{-0.17}(stat)\ ^{+0.07}_{-0.07}(syst)$	0.84

Higgs disappearance

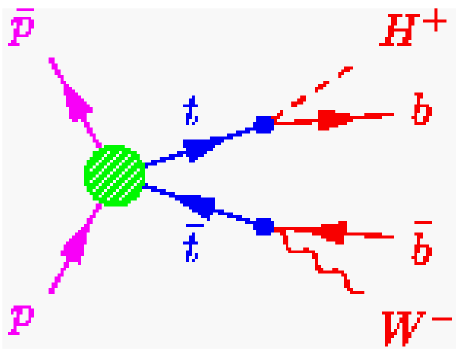
- SM has single Higgs doublet
  - *one physical Higgs: H^0*
- many theories call for two doublets
  - ***SUSY***
  - *other non-SUSY extensions*



five physical states: H^0, h^0, A^0, H^+, H^-

EW interactions specified by:

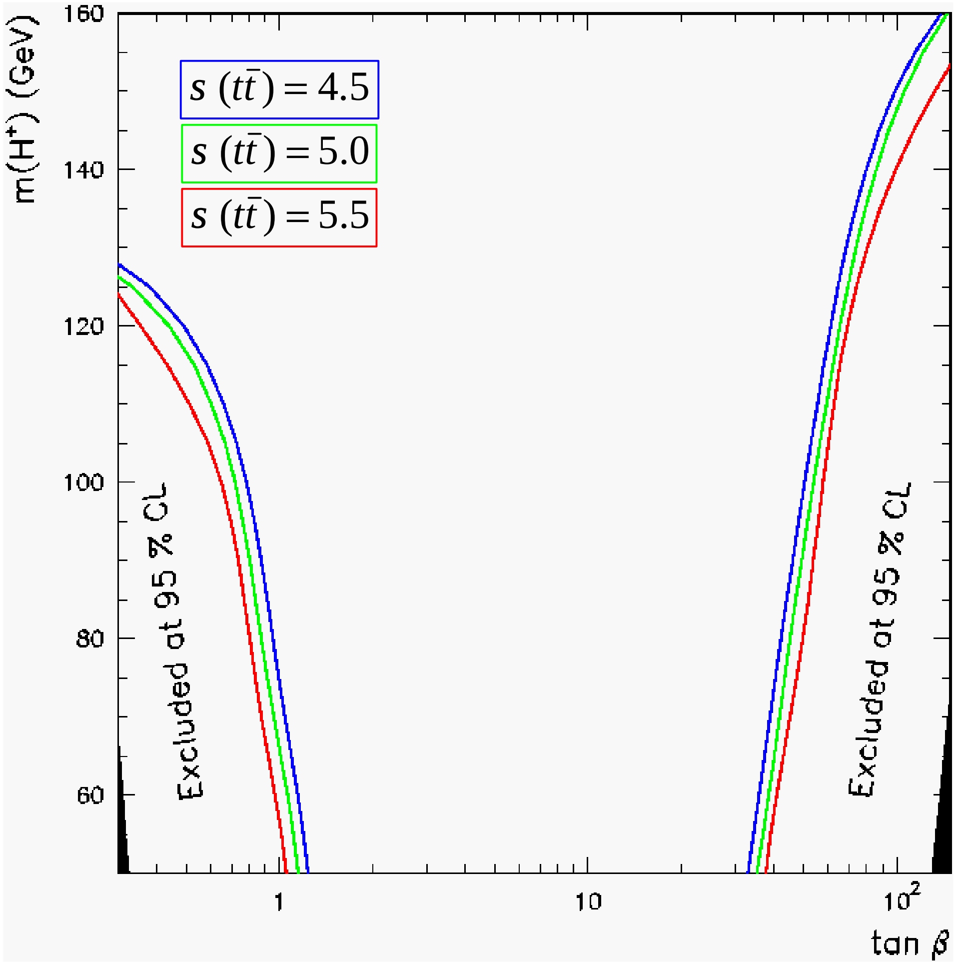
M_W, M_{H^+}, $\tan\beta$



if M_{H^+} is light enough, then $t \rightarrow H^+b$ is open

Higgs disappearance

- $t \to H^+ b$ will compete with $t \to W^+ b$
- can do a disappearance search based on the Lepton + Jets analysis
- for each bin in (m_{H^+}, tan β) space simulate many Monte Carlo experiments
- compare number of expected events with tt lepton + jets data



Higgs disappearance: run II

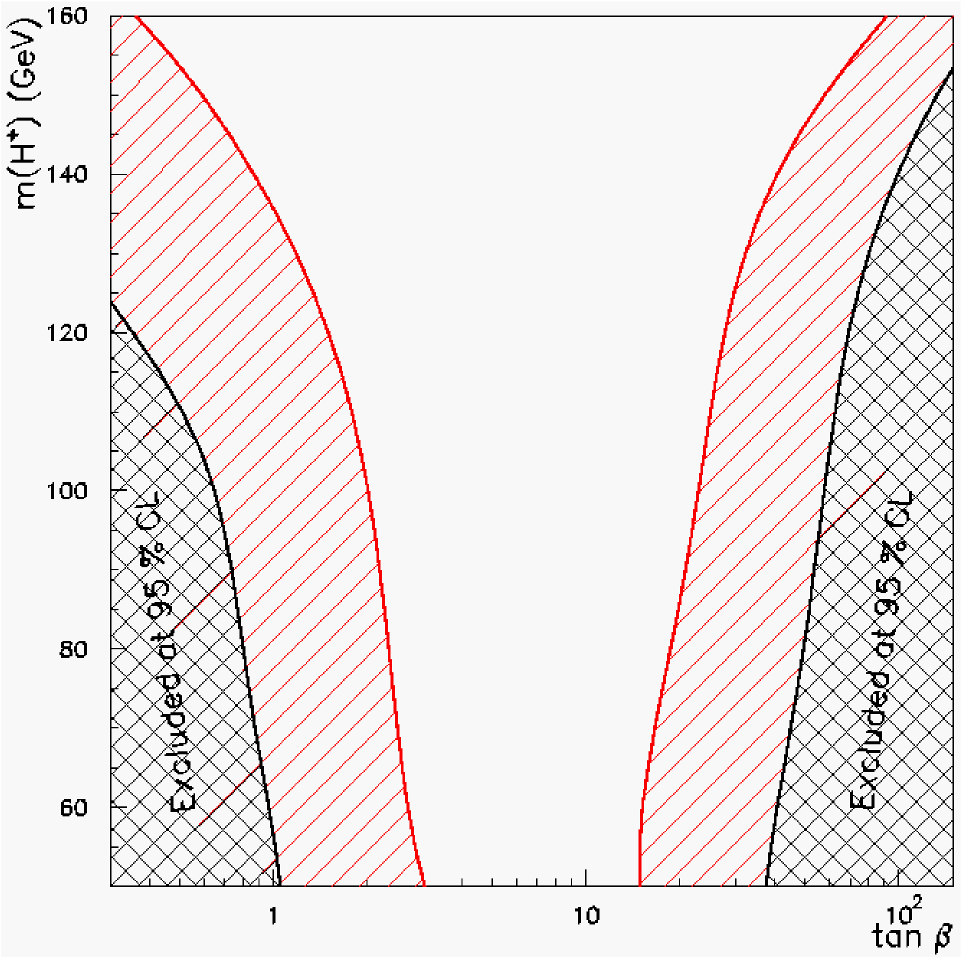
assuming:

$s(t\bar{t}) = 7.0\text{pb}$

$n_{obs} = 600$

$\text{background} = 50 \pm 5$

$e_{SM} = 4.0 \pm 0.4\%$



physics beyond the Standard Model? DØ summary

SUSY

Particle	Signature	Run	DØ 95% confidence level limit (GeV)
W Z	$\not\!\!E_T$+trilepton	Ia	
	$\not\!\!E_T$+trilepton	1a,1b	.66 pb, M(W_1)=45 .01 pb, M(W_1)=124
	$\gamma\gamma+\not\!\!E_T$	1a,1b,1c	.35 pb M(Z_2)-M(Z_1)> 30
q g	$\not\!\!E_T+\geq$3,4 jets	1a	M(g)> 230,heavy squarks
	$\not\!\!E_T+\geq$3 jets	1b	260, M(q)=M(g) *
	$\not\!\!E_T$+dilepton	1b	267 M(q) = M(g) *
	2 e's, 4 jets	1b	280, $\lambda'_{122} \neq 0$, M(q)=M(g) *
	$\gamma+\not\!\!E_T+$ jets	1a,1b,1c	M(g)> 233, heavy squarks * M(q)> 219, heavy gluinos *
t	dilepton+jets	1b	M>93 for M(Z_1)<8
	$\not\!\!E_T$+2 jets	1a	
Sleptons	$\gamma\gamma$ $\not\!\!E_T$	1a,1b,1c	.35 pb M(Z_2)-M(Z_1)> 30
Charged Higgs	top disappearance	1a,1b,1c	$tan\beta < 0.95, M = 50$* $tan\beta > 35, M = 50$* $tan\beta < .11, M = 168$* $tan\beta < 217, M = 168$*
Neutral Higgs	$WH \rightarrow \ell + \not\!\!E_T + b$+jet	1b	*
	$WH, ZH \rightarrow \gamma\gamma$+2 jets	1a,1b,1c	*
	$ZH \rightarrow b$+jet+$\not\!\!E_T$	1a,1b,1c	*

search continues ...

The New York Times

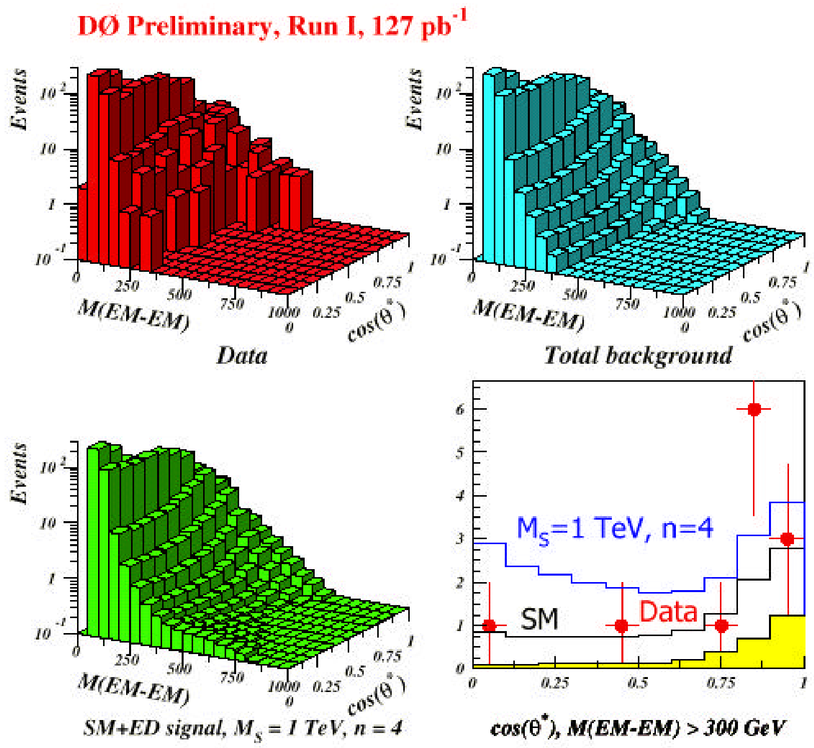
315 Physicists Report Failure In Search for Supersymmetry

The negative result illustrates

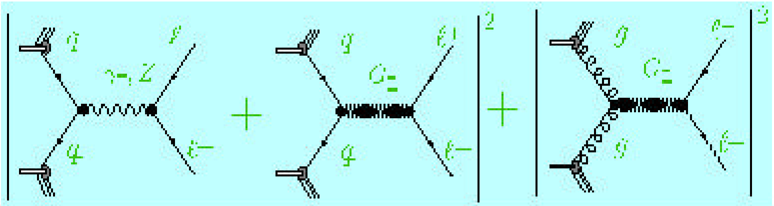
physics beyond the Standard Model? DØ summary

Particle	Signature	Run	DØ 95% confidence level limit (GeV)
b'	2 γ's and 2 jets	1a,1b,1c	$M > M_Z + M_b$
	1 γ, 2 jets, b-tag	1a,1b,1c	$M > M_Z + M_b$
Z'	di-jets	1a,1b,1c	$M < 365$ GeV/c^2, $M > 615$ GeV/c^{2*}
	di-electrons	1b,1c	M>670 GeV/c^{2*}
W'	di-jets	1a,1b,1c	$M < 340$ GeV/c^2, $M > 680$ GeV/c^{2*}
	e ν	1a,1b	$M > 720$GeV/c^2
q^*	di-jets	1a,1b,1c	$M > 725$ GeV/c^{2*}
LQ1, scalar	ee jet jet	1a,1b,1c	$M > 225$ GeV/c^2, $\beta = 1$
	e ν jet jet	1a,1b,1c	$M > 204$GeV/c^2, $\beta = 0.5$
	$\nu\nu$ jet jet	1a	$M > 79$ GeV/c$^2 \beta = 0.$
LQ1, vector	ee jet jet	1a,1b,1c	$M > 340$ GeV/c^2, $\beta = 1$
	e ν jet jet	1a,1b,1c	$M > 329$GeV/c^2, $\beta = 0.5$
	$\nu\nu$ jet jet	1a	$M > 200$ GeV/c$^2 \beta = 0.$
LQ2, scalar	$\mu\mu$ jet jet	1b	$M > 184$ GeV/c^2, $\beta = 1^*$
	$\mu\nu$ jet jet	1b	$M > 140$ GeV/c^2, $\beta = 0.5^*$
LQ3,scalar	bb $\nu\nu$	1b	$M > 94$ GeV/c^{2*}
LQ3,vector	bb $\nu\nu$	1b	$M > 148$ GeV/c^{2*}
monopole	$\gamma\gamma$	1a,1b,1c	610, s=0* 870 s=$\frac{1}{2}^*$ 1580 s=1*

exotics search- large extra spatial dimensions



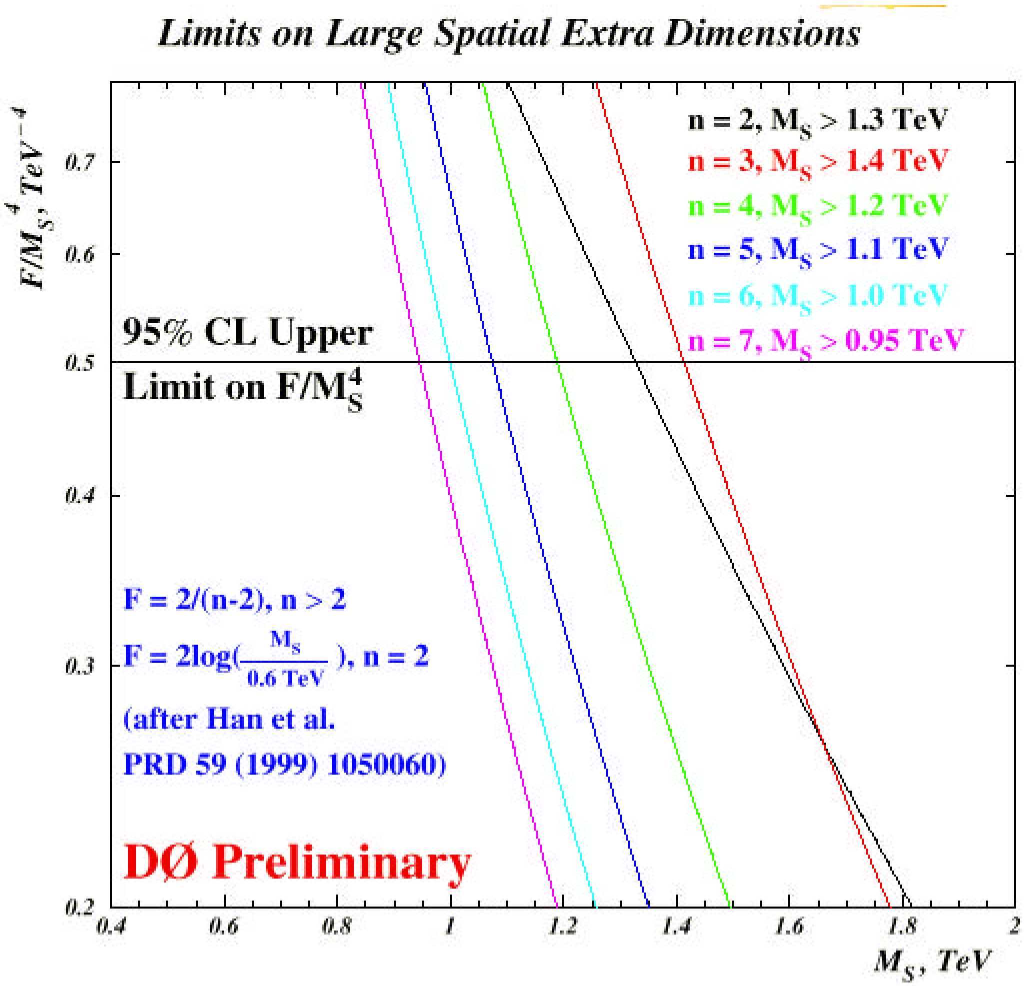
- look for interference with virtual *graviton* in SM Drell-Yan and di-photon production



- spin 2 graviton would also effect angular distributions

  *study M vs cosq**
- data does not support extra dimensions hypothesis
- no excess of events at high mass or low scattering angles
- can set limits

large extra spatial dimensions - limits



For $n > 2$ M_S limits can be obtained directly from η limits

For $n = 2$, use average $\hat{s}$ for gravity contribution ($\langle\hat{s}\rangle = 0.36$ TeV^2, see hep-ph/9909218)

As $n = 2$ case has been ruled out by cosmological constraints, and is within the reach of the current gravity experiments, such an approximation is good enough

Finally, translate limits in Hewett and GRW frameworks for easy comparison with other experiments:

- M_S(Hewett) > 1.1 TeV
- Λ_T(GRW) > 1.2 TeV

This limits are comparable with the final limits expected from LEP2

They are complementary to those from LEP2, as they probe much higher range of $\hat{s}$

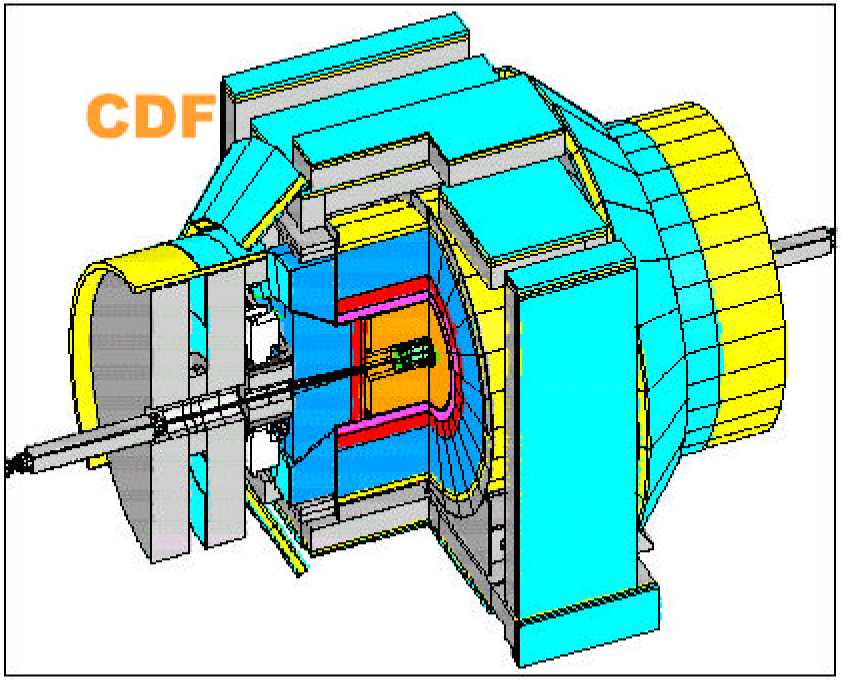
conclusions

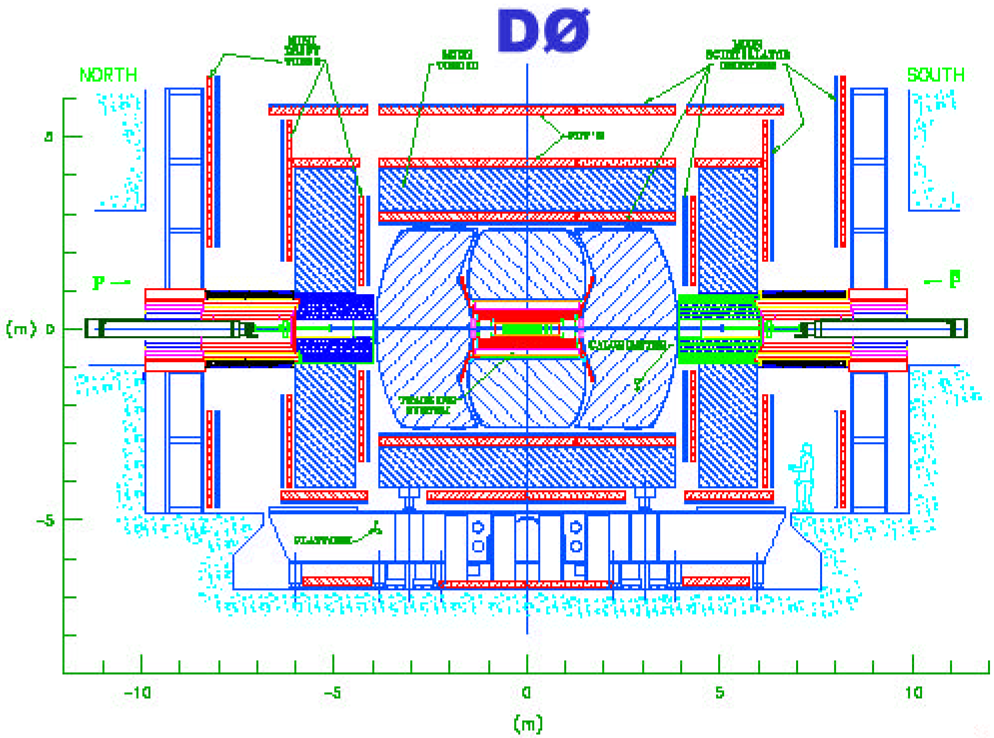
- the top quark is the best measured of any of the known quarks
  - $s(tt)_{CDF} = 6.5^{+1.7}_{-1.4}$ pb
  - $s(tt)_{DØ} = 5.9 \pm 1.7$ pb
  - $m_t = 174.3 \pm 5.1$ GeV/c^2
- we have moved beyond the discovery phase
  - *are already able to characterize properties of the top quark & its decay*
  - *M_{tt}, p_t, spin, W decay, etc.*
- run II outlook is bright for top physics at the Tevatron
  - *dM, dW, dH*
    - *New techniques (Neural Nets)*
  - *rare decays*
  - *top properties (V_{tb}, etc)*
  - *new phenomena reach*

http://www-d0.fnal.gov/

http://www-cdf.fnal.gov/

run II: detector upgrades





- a new massive silicon vertex detector
  - 7 layers extending to 28 cm in radius
  - dead timeless SVX3 readout electronics
- a new central outer tracker
- fast, hermetic scintillator tile plug and forward calorimeter
- large trigger bandwidth

- entirely new tracking system
  - 2T super conductor solenoid
  - disk/barrel silicon detector
  - 8 layers of scintillating fiber tracker
  - preshower detectors
- improved muon spectrometer
- new trigger and DAQ system

summary of top measurements and expectations

Top quark Property	Run 1 measurement	Precision			
		Run 1	Run IIa	Run IIb	LHC
Mass (CDF)	$176.1 \pm 4.2 \pm 5.1\,\mathrm{GeV}/c^2$	3.8%	1.7%	1.0%	1%
Mass (DØ)	$172.1 \pm 5.2 \pm 4.9\,\mathrm{GeV}/c^2$				
Mass (CDF + DØ)	$174.3 \pm 3.3 \pm 3.9\,\mathrm{GeV}/c^2$	2.9%	1.2%	1.0%	
$\sigma_{t\bar{t}}$ (CDF)	$6.5^{+1.7}_{-1.4}\,\mathrm{pb}$	25%	10%	5%	5%
$\sigma_{t\bar{t}}$ (DØ)	$5.9^{+1.7}_{-1.7}\,\mathrm{pb}$				
W helicity, F_0	$0.91 \pm 0.37 \pm 0.13$	0.4	0.09	0.04	0.01
W helicity, F_+	$0.11 \pm 0.15 \pm 0.06$	0.15	0.03	0.01	0.003
$R \equiv \frac{B(t \to Wb)}{B(t \to Wq)}$	$0.94^{+0.31}_{-0.24}$	30%	4.5%	0.8%	0.2%
	> 0.61 at 90% C.L.				
$\lvert V_{tb} \rvert$	$0.96^{+0.16}_{-0.12}$ (3-gen.)				
	> 0.051 at 90% C.L.	> 0.05	> 0.25	> 0.50	> 0.90
σ(single top)	$< 18.6\,\mathrm{pb}$	–	20%	8%	5%
$\Gamma(t \to Wb)$	–	–	25%	10%	10%
$\lvert V_{tb} \rvert$	–	–	12%	5%	5%
$\mathrm{BR}(t \to \gamma q)$ 95% CL	0.03	0.03	2×10^{-3}	2×10^{-4}	2×10^{-5}
$\mathrm{BR}(t \to Zq)$ 95% CL	0.30	0.30	0.02	2×10^{-3}	2×10^{-4}